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BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
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TRANSPORTATION AND DEPOSITION OF HEAVY MINERALS

BY GORDON RITTENHOUSE

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ABSTRACT

An attempt to use heavy minerals to evaluate sediment sources in the Middle Rio Grande Valley showed the inadequacy of commonly used methods of representing heavy-mineral compositions. To develop a usable method, six samples from a transverse channel section were studied by quantitative methods. The size-distribution curves (by weight) of 12 heavy minerals were similar in general form to those of the light minerals, but displaced toward the finer sizes. Among samples the heavy-mineral composition varied systematically with differences in average size and sorting of the light minerals.

The size distribution of a heavy mineral in a fluvial deposit appears to depend on (1) its relative availability in each size grade in the stream load, (2) its equivalent hydraulic size, (3) the hydraulic conditions at the time and place of deposition, and (4) some factor or factors now unknown. In the Rio Grande, the equivalent hydraulic sizes of 16 heavy minerals vary from 1.0ϕ to .2ϕ.

The hydraulic ratio is recommended as a genetically sound method of representing the heavy-mineral composition of sediments. This ratio is the same in the stream load and bed deposits. Changes in the hydraulic ratio caused by wear, selective transportation, and other factors are discussed.

Other methods of representing heavy-mineral compositions are discussed and their limitations outlined. All methods are of limited applicability, but ratios between heavies of about the same specific gravity may be used most extensively. If the limitations are not observed, invalid conclusions may be reached.

INTRODUCTION

Although heavy minerals have been used extensively in attempts to solve a variety of geologic problems, comparatively little is known about the principles or laws that govern their occurrence in sedimentary deposits. Most papers about heavy minerals have been primarily descriptive in character, the particular species present and some data on their relative abundance by number being recorded. In a few investigations, notably those by Pettijohn (1931), Pettijohn and Ridge (1933), Pettijohn and Lundahl (1943), Russell (1937), and Smithson (1939), quantitative data have been obtained on suites of related samples. Some principles of heavy-mineral transportation and deposition have been inferred from the progressive change or lack of progressive change in these series. Perhaps the best paper yet written on the transportation and deposition of heavy minerals, however, was that by Rubey (1933b), who made a theoretical analysis of the relative importance of factors that might influence the size distribution of heavies in water-laid deposits. In contrast to other workers, Rubey used weight, rather than number, as the basis of his reasoning.

A feature common to previous studies has been the adoption of some arbitrary, empirical basis to compare the heavy-mineral composition in the samples examined.

The presence or absence of "diagnostic" mineral species, the relative abundance by number of the mineral species in the heavy-mineral fraction (expressed either as rough scales of abundance or as mutual percentages), and ratios between the number frequencies of selected heavy minerals have been used. Such descriptive values are determined for the whole sample, or for one or more selected size grades of the sample. In a very few studies, methods of comparison were selected after rather critical survey of the then existing data on the occurrence of heavy minerals in sedimentary deposits.

The validity of conclusions reached through the use of such empirical methods is entirely dependent on the validity of the stated or unstated assumptions underlying the conclusions. Basically, these assumptions concern the principles or laws that govern the occurrence of heavy minerals in sedimentary rocks. Consequently, tests of validity, and even recognition of some assumptions yet unknown, depend on a better understanding of fundamental laws governing heavy-mineral occurrence. Unfortunately, the body of comprehensive data needed to provide such understanding has not been available. Accumulation and interpretation of such comprehensive data is, in the writer's opinion, the most important problem now facing sedimentary petrologists who are investigating heavy minerals.

For some time the writer has been engaged in an extensive study of heavy minerals in the Rio Grande and its tributaries in the Middle Valley in New Mexico. In this area, the problems of arroyo trenching and accelerated soil erosion in relation to channel aggradation and other types of injurious sedimentation have been under investigation by the Soil Conservation Service and other governmental and private agencies. It has been found that sediment accumulates in the Middle Valley at a rate of about 12,000 acre-feet annually, that accumulation is more rapid in the channel and floodway than on the flood plain, and that about 75 per cent of the sediment accumulates in the 33 miles of valley below San Acacia, New Mexico. Such sediment deposits, accumulating over a period of years, have caused much damage. Channel and floodway capacity for discharge of flood water has been reduced ground-water tables have been raised, drainage has been impaired, and infertile sand has been deposited on pastures and cultivated lands.

One critical problem in the comprehensive study was the relative importance of different parts of the drainage area as sources of injurious sediment—mainly medium and fine sand. Without reliable data on sediment sources, it would be impossible to plan a sound, economical program of remedial measures. Because methods then in use were very costly, and because sufficiently accurate results would not have been available for some years, it was decided to try to determine the relative importance of sand sources by comparing the heavy-mineral content of tributary streams with that in the main stream above and below the tributary junctions.

After a series of samples had been collected, and the heavy-mineral content determined, it was apparent that heavy minerals could be used for this purpose. But it was also apparent that the empirical methods then in use for representing and comparing the heavy-mineral content of river sands were not suitable for evaluating sediment sources. (*See* section on Hydraulic Ratios.) A new method of representing mineral composition, based on the principles of sediment transportation and de-

position, was needed. The primary purpose of the investigation reported in this article was to develop such a method.[1]

Many factors control the occurrence of light and heavy minerals in river deposits, and their interrelationships are complex. The mineral composition of a stream is dependent on the kind, the amount, and the size of minerals in the source rocks; on the way in which the source rocks are disintegrated; on the absolute and relative rates of mechanical wear and chemical disintegration during transport; on the absolute and relative rates of transportation of different minerals and different sizes of the same mineral; and on the hydraulic conditions that existed at the place and during the time of deposition. At a transverse cross section of a river, however, all these factors except the last will be constants insofar as differences in mineral composition at different places in the cross section may be attributed to them. Their net effect will be reflected in the physical characteristics, availability, and kinds of minerals in the stream load at the cross section. Therefore, these factors and their complex interrelationships need not be considered in explaining why the mineral composition of bed deposits varies from place to place in a cross section. If the factors that do cause such variation can be recognized and their relative importance established, it should be possible to develop a genetically sound method of representing heavy-mineral compositions—a method that would define the mineral composition of the deposits regardless of their texture. The solution of other phases of the broad problem would also be greatly simplified.

This reasoning has been the basis of the investigation reported in this paper. A series of samples were collected from a transverse section of the Rio Grande near Bosque, New Mexico. These samples were sieved, and quantitative number and weight data were obtained for the heavy minerals in seven $\sqrt{2}$ size grades of each of six samples. The heavy minerals were found to have size distributions (by weight) similar in general to those of the light minerals in the same samples but were displaced toward the finer sizes. There seemed little doubt that the size distributions of heavy minerals vary systematically with differences in average size and degree of sorting of the deposits in which they were found.

To determine what factors might control the accumulation of light and heavy minerals at a transverse section, a theoretical analysis was made. The data from the six samples were then analyzed to find whether the actual mineral occurrence could be explained by these factors. It was not possible, in making the assumptions and analyzing the data, to work with each mineral individually because the hydraulic conditions that existed during the accumulation of the sediment and the absolute availability of various sizes of each mineral in the stream load were not known. It seemed probable, however, that under given hydraulic conditions grains of heavy minerals would, because of their greater specific gravity, tend to be deposited with quartz and other light minerals of somewhat larger size. If this were true, avail-

[1] The "hydraulic ratio" method, described in this article, has been used successfully in the Middle Valley and will be widely applicable to other areas where the location of sediment sources is of economic or scientific importance. In the Middle Valley below San Acacia, for example, it was found that the Rio Puerco, which drains about 21 per cent of the area, contributes about 50 per cent of the sediment, and that the Rio Salado, which drains only 6 per cent of the area, contributes about 20 per cent of the sediment. The importance of such data in planning a sediment-control program is obvious. The results of the source investigations will be published elsewhere (Rittenhouse, 1943b; 1943c).

ability could be expressed as relative availability of each heavy mineral with respect to the light minerals that would be deposited with it—*i.e.*, that would be of the same "hydraulic equivalent size." The need for absolute data on hydraulic conditions was also eliminated, because the hydraulic conditions, whatever they may have been, would have been the same for hydraulically equivalent heavy and light minerals that accumulated together.

The experimental data indicate that the distribution of heavy minerals in river deposits is largely dependent on (1) the hydraulic conditions at the place and during the time of deposition, (2) the relative availability of various sizes of each heavy mineral in the stream load, and (3) the hydraulic equivalent size of the heavies. Some additional factor or factors now unknown also affect the occurrence of heavy minerals of high density—*i.e.*, magnetite, ilmenite, and zircon. Heavies of low density are also affected but to a lesser extent.

Because, for low density minerals at least, the relative availability is constant at a transverse section, it may be used as a basis for representing and comparing heavy-mineral compositions. Since it is a ratio between amounts of hydraulically equivalent grains, it may be termed the "hydraulic ratio." For representing mineral compositions, it may be defined as "100 times the weight of a heavy mineral in a known range of sizes, divided by the weight of light minerals of hydraulic equivalent size". Theoretically, this ratio is the same in the stream load and in the bed deposits, and consequently is independent of average size and degree of sorting in the deposits, factors that limit the use of most empirical methods. Because the hydraulic ratio is based on both the number and weight of heavy minerals, it can be used to determine the quantitative importance of sand source areas.

The extent to which the hydraulic ratio will be changed by such factors as wear, weathering, and selective transportation is discussed. Enough data are available to show that the hydraulic ratio will be extremely valuable in helping to isolate and evaluate the other factors that determine the distribution of heavy minerals in stream deposits.

The Bosque data and the principles of heavy-mineral transportation and deposition derived therefrom have been used to outline, for various types of problems, the limitations of commonly used methods of representing heavy compositions. Although the applicability of all commonly used methods appears to be limited, ratios between minerals of about the same specific gravity may be used most widely. For quantitative sediment source evaluations for which both number and weight of heavies must be used, percentages by weight can be employed to a limited extent. Insofar as possible, the conclusions have been verified by applying statistical tests of significance to the Bosque data. An understanding of these limits of applicability is essential for petroleum and other economic geologists, stratigraphers, sedimentary petrologists, and others who may use heavy minerals.

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TECHNIQUE

LABORATORY ANALYSIS AND COMPUTATIONS

In October 1940 a series of eight spot samples (A–H) were collected at approximately evenly spaced intervals across the high water channel of the Rio Grande

TABLE 1.—*Mechanical composition of samples collected October 1940 at Bosque, New Mexico (RG 12)*

Sample	Weight of sample	Distribution by grade sizes (In per cent)										Derived values			
		>.991 mm.	.991–.701 mm.	.701–.495 mm.	.495–.351 mm.	.351–.250 mm.	.250–.175 mm.	.175–.124 mm.	.124–.088 mm.	.088–.061 mm.	<.061 mm.	Q_1	*Md*	Q_3	*So*†
	Grams											*Mm.*	*Mm.*	*Mm.*	
A	102.60	0.4	0.5	1.4	2.7	8.3	31.4	38.0	14.4	2.1	0.7	0.215	0.172	0.136	1.26
B	99.38	.6	.8	2.6	6.4	18.4	30.2	23.8	12.0	3.6	1.7	.268	.193	.144	1.36
C	92.75	.5	.6	2.7	7.3	18.5	26.9	22.8	15.2	3.4	2.1	.268	.195	.134	1.41
D	100.80	2.5	2.4	5.2	8.9	19.4	24.4	23.4	10.7	2.1	.8	.310	.214	.151	1.43
E	100.17	1.4	1.0	2.7	6.0	16.3	29.0	26.6	12.2	3.2	1.4	.254	.193	.142	1.34
F	99.54	.5	.4	1.4	4.5	13.4	25.1	26.7	17.5	5.0	5.4	.234	.170	.119	1.40
F*	62.20	.4	.4	1.5	4.4	12.4	24.4	27.9	18.2	6.3	4.1	.229	.163	.119	1.39
G	99.22	1.9	1.3	4.6	11.1	26.1	27.6	17.6	6.9	1.8	1.1	.320	.237	.173	1.34
H	99.01	2.4	1.7	4.6	9.6	20.6	25.4	18.0	10.6	3.7	3.5	.304	.217	.148	1.43

* Duplicate analysis.

† Sorting coefficient as defined by Trask.

near Bosque, New Mexico. Each spot sample was the core obtained by forcing a 2-inch iron pipe 44 inches in length about 40 inches into the bed deposits. After air drying, each spot sample was split to about 100 grams in a modified Jones-type splitter (Otto, 1937). These test samples were then placed in a nest of standard Tyler sieves, in which the sieve openings increased from fine to coarse approximately as the $\sqrt{2}$. After 14 minutes shaking in a Rotap mechanical shaker, the sand retained on each screen was weighed. The mechanical composition of the eight samples is presented in Table 1.

Each of the seven finest size grades of samples A, D, F, and G, and later of samples B, C, and a duplicate split of sample F, were dried, weighed to 0.5 mg. on an analytical balance, and placed in acetylene tetrabromide (sp. gr. 2.92) in a funnel equipped with rubber tubing and pinchcock. The suspensions were stirred at intervals until a clean separation of the lights that floated and the heavies that sank had been effected. The light and heavy fractions were removed to separate filter papers, washed with alcohol, dried, and weighed to 0.5 mg. Magnetite was removed from the heavy-mineral fractions with a small horseshoe magnet, and the magnetite and the heavies other than magnetite weighed to 0.5 mg. These weight data are presented in Table 2.

A random sample of the nonmagnetic heavies was split out with a microsplit (Otto, 1933) and mounted in canada balsam. Frequencies by number of the various species of heavies in these separates were determined under the petrographic microscope by identifying and counting a randomly selected sample of the grains. A

TABLE 2.—*Weight and percentage of heavy minerals in spot samples collected October 1940 at Bosque New Mexico (RG 12)*

Sample	Size	Weight	Weight of lights	Weight of heavies	Weight of magnetite*	Weight of heavies other than magnetite	Heavies in size grade
	Mm.	*Grams*	*Grams*	*Grams*	*Grams*	*Grams*	*Per cent*
A	>.991	0.36	.....	.....	.....	.....	.....
	.991–.701	.50	.....	.....	.....	.....	.....
	.701–.495	1.46	.....	.....	.....	.....	.....
	.495–.351	2.780$_0$	2.763$_5$	0.008$_5$	0.001$_0$	0.007$_5$	0.3
	.351–.250	8.559$_0$	8.525$_0$	.036$_5$	.005$_5$	.030$_5$	.4
	.250–.175	32.280$_5$	32.164$_5$	.126$_0$	.013$_0$	.112$_5$	.4
	.175–.124	38.912$_5$	38.550$_5$	.392$_0$	.042$_5$	.349$_5$	1.0
	.124–.088	14.748$_5$	14.033$_0$	.696$_5$	.150$_0$	.546$_0$	4.7
	.008–.061	2.147$_0$	1.747$_5$	.398$_5$	.133$_5$	.263$_0$	18.5
	<.061	.732$_5$	.533$_0$	.163$_0$	.044$_0$	.114$_5$	22.2
B	>.991	.55	.....	.....	.....	.....	.....
	.991–.701	.83	.....	.....	.....	.....	.....
	.701–.495	2.57	.....	.....	.....	.....	.....
	.495–.351	6.386$_5$	6.365$_0$	.019$_0$	.004$_0$	.015$_5$	.3
	.351–.250	18.260$_0$	18.128$_5$	.076$_5$	.015$_0$	.061$_5$	.4
	.250–.175	30.102$_0$	29.883$_5$	.204$_0$	.042$_0$	.162$_0$	.7
	.175–.124	23.674$_5$	23.282$_0$	.374$_0$	.065$_0$	.308$_5$	1.6
	.124–.088	11.903$_0$	11.230$_5$	.656$_0$	.209$_5$	.446$_0$	5.5
	.088–.061	3.543$_5$	3.160$_0$	.371$_5$	.142$_0$	.229$_0$	10.5
	<.061	1.692$_5$	1.432$_5$	.196$_0$	.056$_0$	.139$_0$	11.6
C	>.991	.42	.....	.....	.....	.....	.....
	.991–.701	.60	.....	.....	.....	.....	.....
	.701–.495	2.53	.....	.....	.....	.....	.....
	.495–.351	6.750$_0$	6.721$_0$	.014$_5$	.002$_5$	.012$_5$	.2
	.351–.250	17.133$_5$	17.072$_5$	.055$_0$	.010$_5$	.045$_5$	.3
	.250–.175	24.923$_0$	24.783$_0$	.130$_0$	.021$_0$	.110$_0$	.5
	.175–.124	21.155$_5$	20.862$_0$	.283$_0$	.049$_5$	.234$_0$	1.3
	.124–.088	14.110$_0$	13.636$_5$	.454$_5$	.126$_0$	.328$_5$	3.2
	.088–.061	3.171$_5$	2.909$_0$	.247$_0$	.075$_0$	.172$_0$	7.8
	<.061	1.922$_5$	1.648$_0$	.196$_0$	.053$_5$	.140$_5$	10.2
D	>.991	2.46	.....	.....	.....	.....	.....
	.991–.701	2.37	.....	.....	.....	.....	.....
	.701–.495	5.22	.....	.009$_5$	.....	.....	.2
	.495–.351	8.892$_0$	8.859$_5$	.030$_0$	.005$_5$	.023$_5$	.3
	.351–.250	19.507$_0$	19.419$_0$	.106$_0$	.017$_5$	.089$_0$	.5
	.250–.175	24.957$_5$	24.705$_5$	.250$_5$	.055$_5$	.194$_5$	1.0
	.175–.124	23.639$_5$	23.121$_0$	.516$_0$	.144$_0$	.371$_0$	2.2
	.124–.088	10.730$_5$	10.202$_0$	.531$_5$	.146$_5$	.383$_0$	5.0
	.088–.061	2.085$_5$	1.850$_5$	.236$_0$	.075$_5$	.160$_0$	11.3
	<.061	.812$_5$	.669$_5$	.110$_0$	.031$_5$	.076$_0$	13.5

* Includes all material removed with a weak horseshoe magnet.

TABLE 2.—*Continued*

Sample	Size	Weight	Weight of lights	Weight of heavies	Weight of magnetite*	Weight of heavies other than magnetite	Heavies in size grade
	Mm.	*Grams*	*Grams*	*Grams*	*Grams*	*Grams*	*Per cent*
F	>.991	0.47	.....	.....	.....	.....	.....
	.991–.701	.38	.....	.....	.....	.....	.....
	.701–.495	1.43	.....	.....	.....	.....	.....
	.495–.351	4.462$_0$	.....	0.016$_0$	0.003$_0$	0.012$_5$	0.4
	.351–.250	13.353$_5$	13.294$_0$	.056$_5$	.009$_5$	.047$_0$	.4
	.250–.175	24.971$_0$	24.792$_0$	.180$_0$	.027$_5$	.152$_5$	.7
	.175–.124	26.537$_0$	26.005$_0$	.514$_0$	.103$_0$	.411$_0$	1.9
	.124–.088	17.380$_5$	16.622$_0$	.741$_0$	.215$_0$	.526$_0$	4.3
	.088–.061	5.007$_5$	4.626$_5$	.353$_5$	.092$_0$	.260$_5$	7.1
	<.061	5.332$_5$	4.886$_5$	.276$_0$	.072$_0$	.191$_5$	5.2
F†	>.991	.24	.....	.....	.....	.....	.....
	.991–.701	.25	.....	.....	.....	.....	.....
	.701–.495	.96	.....	.....	.....	.....	.....
	.495–.351	2.759$_0$	2.744$_0$	.008$_5$	.000$_5$	.008$_0$	.3
	.351–.250	7.738$_0$	7.689$_5$	.031$_5$	.003$_5$	.028$_0$	.4
	.250–.175	15.151$_0$	15.038$_0$	.094$_0$	.018$_5$	.075$_0$	.6
	.175–.124	17.282$_5$	16.944$_0$	.274$_5$	.060$_5$	.213$_5$	1.6
	.124–.088	11.286$_0$	10.772$_5$	.438$_0$	.142$_5$	.294$_5$	3.9
	.088–.061	3.866$_5$	3.578$_0$	.253$_0$	.074$_0$	.178$_0$	6.5
	<.061	2.525$_0$	2.294$_5$	.174$_0$	.041$_5$	.126$_0$	6.9
G	>.991	1.86	.....	.....	.....	.....	.....
	.991–.701	1.24	.....	.....	.....	.....	.....
	.701–.495	4.580$_0$	.....	.006$_0$	.....	.....	.1
	.495–.351	10.972$_0$	10.939$_5$	.036$_5$	.007$_5$	.029$_5$	.3
	.351–.250	25.853$_5$	25.730$_0$	.139$_0$	.022$_0$	.117$_0$	.5
	.250–.175	27.367$_5$	27.003$_0$	.387$_0$	.087$_5$	.300$_0$	1.4
	.175–.124	17.424$_0$	16.816$_5$	.626$_0$	.210$_0$	.415$_5$	3.7
	.124–.088	6.827$_5$	6.339$_0$	.495$_5$	.187$_0$	.307$_5$	7.3
	.088–.061	1.833$_0$	1.689$_0$	.145$_5$	.042$_0$	.102$_5$	7.9
	<.061	1.080$_0$	.954$_0$	.088$_0$	.018$_0$	.063$_5$	8.1

† Duplicate analysis.

total of 27,630 grains was identified and counted in 49 slides, an average of 594 grains per slide. Grains counted per slide varied from 85 to 1638, the number of grains counted being roughly proportional to the amount by weight of heavies in the sieve separates of the test samples. The number frequency data are presented in Table 3.[2]

Because the clean segregation of each species and variety of heavy mineral from the others is not practical, the size distribution by weight of the various heavies was determined indirectly, using the number frequencies obtained by counting as a basis. The procedure was as follows: For the nonmagnetic heavies in each size grade, the percentage by number of each mineral was multiplied by the specific

[2] The percentages in Table 3 are carried to one decimal place so that the number of grains counted may be computed accurately, if desired. It is recognized that the results are not this accurate for many (perhaps most) minerals.

gravity of that mineral. These number frequency-specific gravity products were summed for all minerals in the sample, and each product then divided by the total, to give the weight percentage of each mineral in the nonmagnetic heavy separate.[3] The total weight of nonmagnetic heavies in the size grade was then multiplied by this weight percentage to give the weight of each species or variety of heavy mineral in the size grade.

Similar computations were made for all size grades in the six samples. The weight of each mineral in each size grade was divided by the total weight of that mineral in that entire sample to give the percentage by weight of that mineral in each size grade. These percentages by weight are similar to and comparable with the weight percentages ordinarily obtained by sieve analyses. These data for the six Bosque samples are presented in Table 4.

SEMILOGARITHMIC PLOT OF SIZE DISTRIBUTION

Having obtained the size distribution of 12 heavy minerals in the 6 samples, the question arises as to how they may be compared with each other and with the size distribution of the light minerals, so that the similarities and differences that give information about the laws of sediment transportation and deposition may be clearly shown. Histograms or block diagrams and cumulative frequency curves have both been used extensively to compare the mechanical composition of sediments. Because cumulative curves have several distinct advantages over histograms for such presentation they are used exclusively here. Many geologists, however, have used histograms almost exclusively and are hazy about the interpretation of cumulative curves. Since a clear understanding of cumulative curves and their meaning is fundamental to understanding the discussions that follow, the relations between the two methods of presentation will be considered in some detail.

In a sand the grains form a continuous series with respect to size—*i.e.*, if all grains in a sample were arranged according to increasing or decreasing diameter, the diameters of adjacent grains would vary by infinitesimals throughout the entire range of sizes present. Since measurement of the diameters of all grains in a sample is usually impractical, the sediment is divided into convenient, but arbitrary, units with sieves. A histogram may then be constructed by erecting adjacent vertical rectangles, proportional in height to the amount of sand in each arbitrary unit, along a base line (Fig. 1). The actual data obtained in the sieve analysis are thus presented, but further extrapolation of that data to approximate the actual continuous distribution of sizes more closely is difficult. Any comparisons between samples are dependent on visual differences that may be apparent to the observer, and can only be made in general terms or through arbitrary methods of computing constants of questionable meaning and value.

The cumulative curve, in contrast, not only presents the actual data obtained from the sieve analysis but provides a better approximation of the actual continuous size distribution of the sample. Small differences in texture between samples are imme-

[3] In this change from number to weight percentage, it was assumed that the relative volumes of all minerals in the size grade were the same. This assumption was roughly checked by comparing the calculated densities with densities determined by pycnometer. For four such comparisons, the values were 3.37 and 3.28, 3.44 and 3.38, 3.34 and 3.31, and 3.47 and 3.42, the calculated value being the smaller in each case.

TABLE 3.—*Frequency by number of heavy minerals other than magnetite in samples collected October 1940 at Bosque, N. M. (RG 12)*

(In per cent)

Sample	Size grade	Grains counted	Ilmenite	Pyroxene	Hypersthene	Diopside (C)	Diopside (Br)	Blue-green hornblende	Green hornblende	Brown hornblende	Epidote	Tourmaline	Zircon	Micas	Apatite	Garnet	Monazite	Titanite	Barite	Staurolite	Kyanite	Altered	Rock fragments	Calcite	Quartz and feldspar	Unknown†
	Mm.	*Number*																								
A	.495–.351	85	.....	4.7	.....	.....	.....	5.9	.....	.....	5.9	.....	.....	51.8	.....	1.2	.....	.....	.....	.....	1.2	21.2	2.4	.....	4.7	1.2
	.351–.250	246	1.2	3.3	0.8	0.4	0.8	2.4	0.4	.....	2.9	0.4	.....	56.9	.....	1.2	.....	.....	.....	.....	.8	22.8	5.3	.....	.4	.....
	.250–.175	429	2.6	9.6	3.5	1.6	1.2	10.5	5.8	1.2	2.8	.2	.....	12.1	0.5	.2	.....	0.5	0.2	.....	.5	35.7	7.7	0.2	.7	2.6
	.175–.124	697	6.0	7.6	2.7	2.0	2.0	14.9	5.2	2.0	6.0	2.0	0.4	2.3	1.0	.7	0.3	1.3	.7	0.4	.4	30.6	7.0	.3	.1	3.9
	.124–.088	1,208	25.5	5.4	3.5	1.3	1.2	7.0	5.1	1.3	6.5	2.2	1.5	1.7	2.7	2.2	.4	.9	.5	.3	.4	14.0	6.1	1.7	5.7	2.7
	.088–.061	1,290	50.4	3.8	1.5	.9	.5	3.1	2.8	1.1	5.2	1.6	6.6	.4	1.7	1.9	.1	1.0	.9	.2	.1	9.4	3.6	.5	1.3	1.6
	<.061	895	63.2	2.7	1.3	.6	.3	1.3	.9	.1	1.9	1.2	11.4	.1	3.0	2.5	.....	.3	1.1	.....	.1	3.6	1.2	.....	.8	2.2
B	.495–.351	168	.6	8.3	1.8	.....	.6	3.0	.....	.6	1.2	.....	.....	48.8	.....	1.8	.....	1.2	.....	.....	.....	21.4	7.7	.....	.....	3.0
	.351–.250	166	5.4	15.7	2.4	.6	.....	7.8	.6	.....	3.0	1.2	.....	18.1	.6	1.2	.....	1.2	.....	.....	.6	30.7	9.0	.....	.....	1.8
	.250–.175	396	6.3	9.6	3.0	1.3	.5	9.6	4.6	.8	6.3	.8	.....	8.1	1.0	1.3	.3	1.3	.....	.3	.5	27.3	13.9	.....	.5	3.0
	.174–.124	557	10.4	9.7	2.0	2.9	2.9	12.6	4.7	1.8	5.9	1.3	.4	2.7	1.4	2.7	.4	1.6	.4	1.4	.4	20.8	10.2	.2	.4	3.1
	.124–.088	639	31.8	5.8	.5	2.0	.2	8.9	4.4	1.6	5.6	1.7	2.4	.2	1.9	2.8	.2	1.6	1.4	.8	.5	16.8	5.3	.....	.3	3.6
	.088–.061	877	40.0	5.4	1.4	.8	.3	5.0	4.1	1.8	4.5	2.5	6.0	.2	1.7	1.0	.....	2.1	1.3	.5	.....	13.1	4.2	.3	.2	3.5
	<.061	444	34.9	3.8	.9	1.6	.9	6.1	4.5	2.5	2.7	1.8	11.3	.....	1.8	.7	.....	1.1	1.4	.5	.....	12.6	6.8	.5	.5	3.4
C	.495–.351	150	.7	6.7	.7	.....	.....	2.0	.....	.....	5.3	.....	.....	53.3	.....	.....	.....	.....	.....	.....	.....	28.0	2.7	.....	.....	.7
	.351–.250	237	1.3	10.1	1.3	.8	1.3	8.9	3.4	.4	2.1	.....	.....	23.2	1.7	.....	.....	.....	.....	.....	.....	36.3	7.6	.....	.8	.8
	.250–.175	373	3.2	13.9	1.6	1.3	1.3	8.3	4.3	.5	5.9	.5	.....	11.8	.5	.8	.....	1.1	.....	.5	.8	28.2	11.3	.3	.8	3.0
	.175–.124	438	7.8	10.7	2.5	1.4	.9	13.5	5.9	1.4	5.7	1.8	.2	3.9	1.6	.9	.....	1.6	.2	.5	1.1	21.2	13.7	.....	.2	3.2
	.124–.088	686	17.9	7.4	1.8	1.6	2.2	11.7	4.4	2.6	6.9	2.3	.4	1.7	1.9	2.6	.....	2.0	.6	.9	.2	17.2	8.6	.2	1.0	3.9
	.088–.061	651	28.1	6.0	1.2	1.1	.6	5.8	5.7	1.7	2.2	3.5	5.8	.5	3.7	2.3	.3	1.5	1.1	.6	.....	15.7	6.9	1.4	1.2	3.1
	<.061	637	38.6	4.1	1.4	1.6	.3	3.6	4.4	1.3	2.5	2.2	11.3	.2	3.5	1.1	.2	2.5	1.4	.....	.....	11.5	3.6	.5	.5	3.9
D	.495–.351	94	3.2	6.4	2.1	.....	.....	5.3	2.1	1.1	3.2	.....	.....	22.3	.....	3.2	.....	2.1	.....	.....	.....	41.5	6.4	.....	1.1	.....
	.351–.250	191	8.4	7.9	1.1	.5	.....	7.9	2.1	.....	5.8	.5	.....	9.4	.5	4.2	.....	1.6	.....	.....	.5	35.6	10.5	.5	.....	3.1
	.250–.175	303	16.8	9.2	5.0	2.0	.3	12.5	4.3	1.3	4.6	.3	.....	4.0	1.0	2.0	.....	1.3	.3	.3	.3	24.1	6.6	.....	.3	3.3
	.175–.124	582	18.4	10.0	2.4	1.6	2.6	9.1	5.5	2.2	5.2	2.4	.3	1.6	1.2	2.2	.3	1.4	.2	1.6	.5	18.7	7.9	.....	1.2	3.6
	.124–.088	1,350	28.4	5.9	1.9	1.0	.5	6.2	3.6	2.0	3.7	1.6	1.3	1.0	2.1	1.1	.7	1.2	.9	.7	.2	14.7	7.6	5.7	6.7	1.6
	.088–.061	614	44.5	3.8	1.0	1.5	.8	4.1	3.9	2.4	5.9	1.3	7.7	.2	3.8	2.0	.3	.7	.7	.3	.2	9.8	2.8	.2	.5	2.1
	<.061	581	42.5	3.6	1.4	.9	.3	2.9	2.9	.7	2.4	1.4	16.4	.....	4.8	1.2	.....	.5	1.2	.3	.3	10.2	2.8	.3	.7	2.2
F	.495–.351	93	3.2	9.7	.....	1.1	2.2	2.2	1.1	1.1	4.3	1.1	.....	8.6	1.1	1.1	.....	.....	.....	.....	1.1	41.9	8.6	.....	10.8	1.1

F	.495-.351	93	3.2	9.7	.....	1.1	2.2	2.2	1.1	1.1	4.3	1.1	.....	8.6	1.1	1.1	.....	.....	.....	.....	1.1	41.9	8.6	.....	10.8	1.1
	.351-.250	275	5.1	9.1	1.5	1.1	.4	10.6	4.0	.7	4.7	.4	.....	10.9	1.5	3.3	.....	.4	.....	.4	2.6	35.3	6.6	.....	.....	1.8
	.250-.175	466	8.4	8.8	2.2	1.1	1.3	13.5	4.7	1.9	2.6	1.5	.....	8.2	.....	.9	.....	.6	.4	.2	.2	28.5	10.9	.2	.4	3.4
	.175-.124	720	15.1	5.4	2.5	.7	1.5	11.5	3.9	1.8	5.3	1.7	.7	5.6	1.5	1.5	.6	1.8	.1	1.1	.6	21.4	9.6	1.4	2.5	2.2
	.124-.088	1,509	25.2	4.8	1.9	1.3	1.1	8.1	5.7	2.1	4.8	1.5	1.7	2.8	2.3	2.5	.5	1.5	.5	.1	.7	16.6	5.8	3.1	3.4	2.3
	.088-.061	1,638	25.0	3.2	2.5	1.4	.7	4.6	4.3	1.8	5.5	2.0	3.7	1.0	2.9	1.7	.....	.9	1.3	.1	.5	17.5	6.3	6.7	3.8	2.7
	<.061	878	40.1	2.3	1.3	.6	.2	2.3	2.9	1.3	4.6	1.3	10.8	.9	2.7	2.4	.....	.3	.6	.....	.1	11.4	2.4	2.2	7.3	2.3
F*	.495-.351	57	1.8	12.3	.....	1.8	.....	7.0	1.8	.....	10.5	.....	.....	22.8	.....	3.5	.....	.....	.....	.....	.....	24.6	12.3	.....	.....	1.8
	.351-.250	224	2.7	11.6	3.6	1.3	.5	7.1	2.7	.....	4.9	1.3	.....	13.0	.5	1.8	.....	.5	.....	.....	.5	34.4	11.6	.....	.....	2.2
	.250-.175	200	7.5	10.5	2.5	1.0	2.0	14.0	5.5	1.0	2.0	1.5	.....	14.5	.....	2.0	.5	1.0	.....	.....	.5	19.0	11.0	.5	1.0	2.5
	.175-.124	395	14.2	6.1	2.3	1.3	2.5	14.7	6.6	2.5	6.6	1.0	.....	2.5	1.8	1.3	.3	1.5	.5	.5	1.5	18.7	9.1	.3	1.3	3.0
	.124-.088	778	26.2	6.7	1.2	1.2	.4	9.5	4.2	2.4	5.7	2.7	.9	.3	2.4	2.1	.8	1.9	1.0	.5	.8	19.0	5.0	.....	1.5	3.6
	.088-.061	615	27.3	5.5	1.5	1.6	.7	6.3	6.5	3.3	6.5	1.0	4.1	.....	3.4	1.6	.....	2.4	1.8	.3	.3	12.9	5.7	.....	2.1	5.2
	<.061	452	39.2	4.9	1.1	.7	.4	3.8	5.1	1.8	2.4	1.1	10.6	.....	4.0	1.3	.....	1.6	1.6	.4	.....	11.3	4.2	.....	1.6	3.1
G	.495-.351	110	.9	9.1	.....	.9	.9	6.4	1.8	.9	7.3	.....	.....	14.6	.....	2.7	.....	.....	.....	.....	1.8	40.9	10.9	.....	.....	.9
	.351-.250	326	5.5	13.8	1.5	1.2	.....	7.7	5.2	.9	6.1	.3	.3	4.0	1.2	1.8	.3	.9	.....	.3	.....	35.3	11.7	.....	.3	1.5
	.250 .175	397	17.1	8.6	4.0	1.3	2.0	8.8	5.5	.8	3.0	.3	.3	2.3	1.0	3.5	.....	1.3	.5	.3	.3	28.5	7.3	.8	.....	2.8
	.175-.124	783	35.8	6.5	1.9	1.5	.6	6.8	3.5	1.7	4.6	.5	.9	2.2	1.7	3.6	.5	1.4	.4	.1	.3	18.7	4.7	.3	.1	1.9
	.124-.088	1,126	45.8	4.7	2.1	1.7	.9	6.2	4.6	1.0	5.1	1.7	2.0	.5	1.3	1.4	.1	2.0	.4	.3	.2	10.1	5.7	.1	.2	1.9
	.088-.061	1,076	38.5	4.4	2.2	.7	1.6	4.7	4.1	1.9	3.7	2.7	4.5	.2	2.7	2.2	.2	1.4	1.4	.7	.6	13.5	4.8	1.0	.1	2.3
	<.061	528	42.8	4.9	3.0	.....	.6	3.2	2.7	1.5	3.0	1.7	9.5	.4	2.5	1.5	.....	1.3	1.9	.6	.2	9.3	3.6	1.9	.2	3.8

* Duplicate analysis.

† Unknowns include small quantities of such minerals as zoisite, sillimanite, andalusite, rutile, and topaz.

TABLE 4.—*Frequency by weight of heavy minerals in samples collected October 1940 at Bosque, New Mexico (RG 12)*

Mineral	Sample or derived factor	Weight of mineral in sample	Distribution by size grades (In per cent) .495–.351 mm.	.351–.250 mm.	.250–.175 mm.	.175–.124 mm.	.124–.088 mm.	.088–.061 mm.	<.061 mm.	Derived values Q_1	Md	Q_3	So^{**}
		Gm.								*Mm.*	*Mm.*	*Mm.*	
Magnetite	A	0.389₅	0.3	1.4	3.3	10.9	38.5	34.2	11.3	0.112	0.090	0.075	1.22
	B	.533₅	.7	2.8	7.9	12.2	39.3	26.6	10.5	.122	.099	.077	1.26
	C	.337₅	.7	3.1	6.2	14.5	37.3	22.2	15.9	.125	.100	.073	1.31
	D	.476₀	1.2	3.6	11.6	30.2	30.7	15.8	6.6	.159	.121	.091	1.32
	F	.522₀	.6	1.8	5.3	19.7	41.2	17.6	13.8	.129	.103	.081	1.26
	F*	.340₅	.2	1.0	5.4	17.8	41.9	21.7	12.0	.123	.102	.079	1.25
	G	.574₀	1.3	3.8	15.2	36.6	32.6	7.3	3.1	.170	.132	.106	1.27
	Mean†		.8	2.7	8.2	20.7	36.6	20.6	10.2		.107		
	Coefficient of variation		47.	36.	54.	51.	11.	45.	46.		15.		
Ilmenite	A	.4469		.2	1.0	6.5	40.6	34.1	17.5	.101	.087	.070	1.20
	B	.4082	.1	1.2	3.6	10.9	43.2	26.8	14.3	.111	.094	.075	1.22
	C	.2355	.1	.4	2.2	10.9	33.4	25.8	27.1	.108	.086	.058	1.37
	D	.4081	.3	2.6	10.9	22.3	34.5	20.4	9.1	.140	.110	.085	1.28
	F	.4575	.1	.8	4.0	18.7	37.9	18.5	20.0	.123	.098	.070	1.33
	F*	.2885	.1	.4	2.9	14.4	34.2	21.2	26.8	.117	.090	.059	1.41
	G	.5094	.1	1.8	13.6	36.1	32.9	9.3	6.2	.158	.126	.099	1.26
	Mean†		.1	1.2	5.9	17.6	37.1	22.5	15.7		.100		
	Coefficient of variation			76.	87.	61.	11.	38.	48.		15.		
Pyroxene	A	.0790	.6	1.6	14.8	34.3	35.1	10.5	3.0	.160	.127	.100	1.26
	B	.0968	1.8	10.8	16.8	30.9	24.0	10.9	4.8	.190	.139	.102	1.37
	C	.0864	1.3	6.0	19.1	29.8	27.3	10.9	5.7	.178	.133	.100	1.33
	D	.0908	1.9	8.0	19.5	39.3	23.1	5.6	2.5	.187	.146	.117	1.26
	F	.0774	1.7	5.8	18.1	28.7	30.6	10.2	4.5	.177	.131	.100	1.33
	F*	.0601	1.8	5.8	14.0	21.4	30.3	15.0	11.5	.161	.114	.087	1.36
	G	.0880	3.4	19.0	28.4	27.6	14.2	4.4	3.0	.243	.177	.130	1.37
	Mean†		1.8	8.5	19.4	31.8	25.7	8.7	3.9		.142		
	Coefficient of variation		51.	70.	24.	12.	28.	34.	31.		13.		
Brown hornblende	A	0.0167			7.8	40.1	38.3	13.2	0.6	0.149	0.122	0.100	1.22
	B	.0186	.5		6.4	28.0	31.7	18.3	15.1	.140	.107	.077	1.36
	C	.0156		1.3	3.8	19.9	50.0	16.0	9.0	.124	.107	.088	1.19
	D	.0204	1.5		11.8	36.8	32.8	15.2	2.0	.157	.124	.096	1.28
	F	.0260	.4	1.2	11.1	26.9	36.9	15.8	7.7	.145	.113	.089	1.28
	F*	.0194			4.1	25.8	32.4	25.2	12.4	.132	.100	.075	1.33
	G	.0141	2.1	7.8	14.9	41.1	17.0	11.3	5.7	.175	.145	.105	1.29
	Mean†		.7	1.7	9.3	32.1	34.4	15.0	6.7		.120		
	Coefficient of variation		123.	180.	44.	26.	31.	15.	77.		12.		
Tourmaline	A	.0216		.9	1.4	30.1	48.6	14.3	4.5	.130	.111	.093	1.18
	B	.0182		3.8	6.6	19.2	34.6	24.7	11.0	.133	.103	.077	1.31
	C	.0187			3.2	21.4	35.8	26.7	12.8	.123	.098	.074	1.29
	D	.0164		2.4	3.7	48.2	31.1	9.8	4.9	.148	.128	.102	1.20
	F	.0219	.5	.9	10.0	28.3	31.5	20.1	8.7	.146	.111	.085	1.31
	F*	.0129		3.1	8.5	14.7	52.0	10.9	10.9	.127	.111	.093	1.17
	G	.0098		3.1	7.1	17.4	41.9	22.5	8.2	.129	.104	.083	1.25
	Mean†		.1	1.8	5.3	27.4	37.2	19.7	8.3		.109		
	Coefficient of variation			65.	59.	41.	14.	33.	40.		10.		
Zircon	A	.0458				4.5	22.7	42.6	30.2	.090	.072	.058	1.25
	B	.0489				3.1	26.2	33.1	37.6	.092	.070	.052	1.33
	C	.0332				2.1	5.7	37.0	55.1	.074	.058		
	D	.0360				4.5	18.0	38.9	38.6	.086	.068	.053	1.27
	F	.0513				7.4	21.8	23.6	47.2	.082	.064		
	F*	.0328					10.1	27.2	62.8	.071	.051		
	G	.0256		2.0	3.9	17.6	28.5	21.1	26.9	.122	.092	.058	1.45
	Mean†			.3	.6	6.5	20.5	32.7	39.3		.071		
	Coefficient of variation					88.	40.	26.	18.		16.		
Hypersthene	A	.0367		.8	11.7	26.7	48.7	8.7	3.3	.143	.118	.101	1.19
Apatite	A	.0231				2.2	14.7	57.1	15.1	10.8	.130	.105	.087	1.18

Coefficient of variation			51.	70.	24.	12.	28.	34.	31.		13.		

Coefficient of variation					88.	40.	26.	18.		16.			

Hypersthene	A	.0367		.8	11.7	26.7	48.7	8.7	3.3	.143	.118	.101	1.19
	B	.0190	2.1	8.2	27.4	32.1	10.0	14.2	5.8	.201	.150	.106	1.38
	C	.0179	.6	3.9	10.6	33.5	31.2	10.6	9.5	.156	.122	.094	1.29
	D	.0285	2.1	3.5	33.3	30.2	23.2	4.6	3.2	.202	.154	.117	1.31
	F	.0319		2.2	10.7	32.3	29.2	19.1	6.6	.152	.118	.087	1.32
	F*	.0151		7.3	13.2	31.8	21.2	15.9	10.6	.167	.128	.085	1.40
	G	.0299		6.0	39.4	23.7	18.7	6.7	5.3	.211	.166	.116	1.35
Mean†				.8	4.1	22.2	29.7	26.8	10.6	5.6		.138	
Coefficient of variation				130.	55.	58.	13.	49.	50.	42.		15.	
Blue-green hornblende	A	.1048	.5	.9	11.6	47.8	32.2	6.1	1.1	.147	.119	.100	1.21
	B	.1075	.6	4.6	14.3	33.9	31.3	8.7	6.4	.164	.129	.100	1.28
	C	.0920	.3	4.8	10.1	33.1	38.0	9.4	4.5	.153	.122	.100	1.24
	D	.0891	1.5	7.7	25.4	34.3	23.3	5.8	1.9	.170	.138	.104	1.28
	F	.1220	.3	4.0	16.6	36.6	31.0	8.7	2.9	.142	.111	.092	1.24
	F*	.0816	.5	2.5	13.0	35.8	29.9	11.9	6.2	.160	.127	.096	1.29
	G	.0797	2.4	11.0	30.4	29.7	19.5	5.0	2.0	.217	.160	.114	1.38
Mean†				.9	5.5	18.1	35.9	29.3	7.3	3.1		.130	
Coefficient of variation				95.	63.	44.	17.	23.	26.	51.		13.	
Green hornblende	A	.0555		.4	12.1	31.2	44.7	10.5	1.3	.146	.119	.100	1.21
	B	.0505		.8	14.5	26.9	32.7	15.1	10.1	.153	.114	.088	1.32
	C	.0464		3.7	10.3	28.9	28.2	18.1	10.8	.153	.114	.083	1.36
	D	.0472	1.1	3.8	16.3	39.2	25.4	10.6	3.6	.169	.137	.103	1.28
	F	.0652	.2	2.9	10.9	23.0	41.0	15.3	6.8	.174	.113	.091	1.38
	F*	.0459	.2	1.7	9.2	28.6	23.8	21.6	15.1	.148	.107	.074	1.41
	G	.0500	1.2	11.8	30.4	24.2	23.0	6.8	2.6	.218	.158	.112	1.40
Mean†				.4	3.9	15.7	28.9	32.5	12.7	5.9		.126	
Coefficient of variation				140.	106.	48.	19.	24.	35.	68.		12.	

Apatite	A	.0231			2.2	14.7	57.1	15.1	10.8	.120	.105	.087	1.18
	B	.0185		2.2	8.7	22.7	38.4	17.3	10.8	.135	.108	.084	1.27
	C	.0200		4.0	3.0	18.0	28.5	27.0	19.5	.124	.092	.067	1.36
	D	.0210		2.4	8.6	19.0	33.3	22.8	13.8	.132	.101	.077	1.31
	F	.0281	.4	2.5		21.0	37.3	23.5	15.3	.123	.099	.074	1.29
	F*	.0205		.5		17.1	30.7	25.4	26.3	.114	.086	.060	1.38
	G	.0168		8.3	16.7	34.5	19.6	13.7	7.1	.175	.140	.095	1.36
Mean†				.1	3.2	6.5	21.6	35.7	19.9	11.2		.107	
Coefficient of variation					87.	94.	32.	35.	27.	27.		16.	
Garnet	A	.0236	.4	2.5	1.3	12.3	52.5	20.3	10.6	.116	.099	.085	1.17
	B	.0288	1.4	3.1	8.3	32.3	43.7	8.0	3.1	.145	.120	.102	1.19
	C	.0183			6.0	13.1	50.8	21.9	8.2	.120	.101	.085	1.19
	D	.0264	3.4	16.3	15.9	33.7	16.7	11.0	3.0	.210	.158	.113	1.36
	F	.0334	.6	5.4	4.5	21.0	41.9	13.5	13.2	.143	.120	.101	1.19
	F*	.0172	2.3	3.5	10.5	17.4	36.6	17.4	12.2	.142	.106	.081	1.32
	G	.0372	2.7	6.7	30.9	40.1	11.3	5.9	2.4	.181	.135	.106	1.31
Mean†				1.4	5.7	11.1	25.4	36.1	15.1	6.7		.122	
Coefficient of variation				98.	100.	98.	46.	47.	61.	68.		18.	
Titanite	A	.0127			4.7	37.0	37.8	18.1	2.4	.142	.118	.094	1.23
	B	.0204	.5	3.9	10.8	25.5	31.4	20.6	6.9	.152	.114	.086	1.33
	C	.0176			7.4	22.7	38.1	14.2	17.6	.131	.105	.078	1.30
	D	.0153	3.9	9.8	17.0	32.7	28.8	5.9	2.0	.191	.141	.111	1.31
	F	.0196		1.0	5.6	38.8	39.8	11.7	3.1	.147	.120	.097	1.23
	F*	.0160		.6	5.0	20.6	33.8	25.6	14.4	.126	.097	.074	1.30
	G	.0178		6.2	21.3	30.3	30.9	7.3	3.9	.181	.137	.104	1.32
Mean†				.7	3.5	11.1	31.2	34.5	13.0	6.0		.122	
Coefficient of variation					113.	60.	23.	14.	45.	99.		11.	

* Duplicate analysis.

† Mean and standard error do not include data from duplicate analysis of sample F.

** Sorting coefficient as defined by Trask.

diately apparent from the slope and position of the curves, and these differences may be expressed by constants read directly from the cumulative curve. Such curves and constants have been used extensively in statistics, and rigorous methods of comparing them and of determining the sampling errors to which they are subject

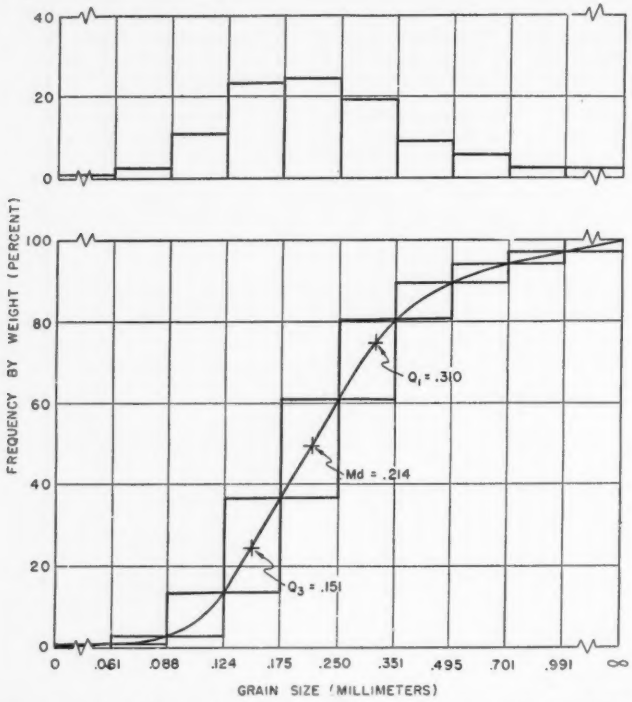

FIGURE 1.—*Mechanical composition of sample A plotted as histogram and a cumulative curve*

are available. In addition, the cumulative curves are independent of the particular arbitrary sieve units selected and thus facilitate comparisons of data obtained with different arbitrary units.

The relation between the histogram and cumulative curve is demonstrated in Figure 1. Instead of placing all rectangles that represent the relative amounts of sediment in the various size grades along the base line of the diagram, as with a histogram, the cumulative curve is formed by arranging the rectangles en echelon and connecting the points of contact with a continuous smooth curve. The result is the best approximation of the actual continuous size distribution in the sample that may be made from the data obtained through the use of arbitrary subdivisions. Such constants as the median and quartiles may be read directly from this curve.

In analyzing and presenting sedimentary data, extensive use is made of semilogarithmic diagrams. In such diagrams, percentage by weight is plotted on an arith-

metic scale against the logarithm of the grain diameters. To eliminate the need for looking up the logarithms of the grain diameter, and thus to facilitate more rapid plotting and easier interpretation of the data, it is common practice to place the values of the grain diameters and not their logarithms along the margin of the diagram. Thus, in Figure 1, the logarithms of the grain diameters rather than the actual grain diameters were plotted for both the histogram and cumulative curve.

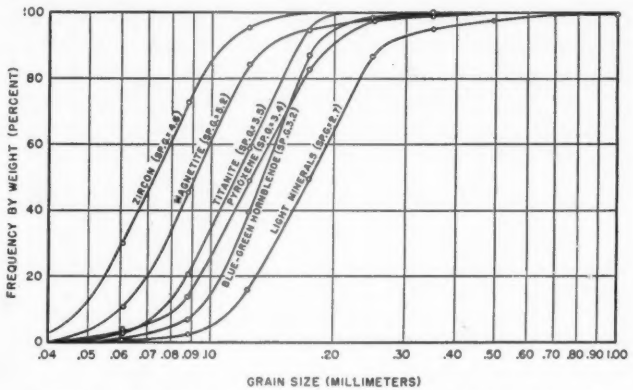

FIGURE 2.—*Size distribution by weight of light and selected heavy minerals*

Sample A

HEAVY-MINERAL SIZE DISTRIBUTIONS

SAME SAMPLE

The size distribution by weight, as determined for 12 heavy minerals in the 6 samples, is presented in Table 4. To illustrate differences in size distribution of various minerals within a single sample, the cumulative curves for the light minerals, and for blue-green hornblende, pyroxene, titanite, magnetite, and zircon in sample A have been plotted in Figure 2.

Several facts are apparent: (1) The size distributions of the heavy minerals form smooth cumulative curves of the same general shape as the cumulative curve of the light minerals; (2) all heavy minerals are finer in texture than the light minerals; (3) in general, increasing specific gravity is accompanied by increasing fineness of the heavy minerals; (4) zircon (sp. gr. = 4.6) is much finer than magnetite (sp. gr. = 5.2); and (5) difference in slope of the curves indicates that heavy minerals in the same sample have different sorting.

DIFFERENT SAMPLES

The size distribution of magnetite, ilmenite, blue-green hornblende, zircon, pyroxene, and all light minerals considered as a group has been plotted for samples A, D, F, and G in Figure 3. The heavy minerals of these four samples vary both in average size of grain and sorting in the four samples, and, in general, these differences are remarkably similar to those exhibited by the light minerals. Sample G,

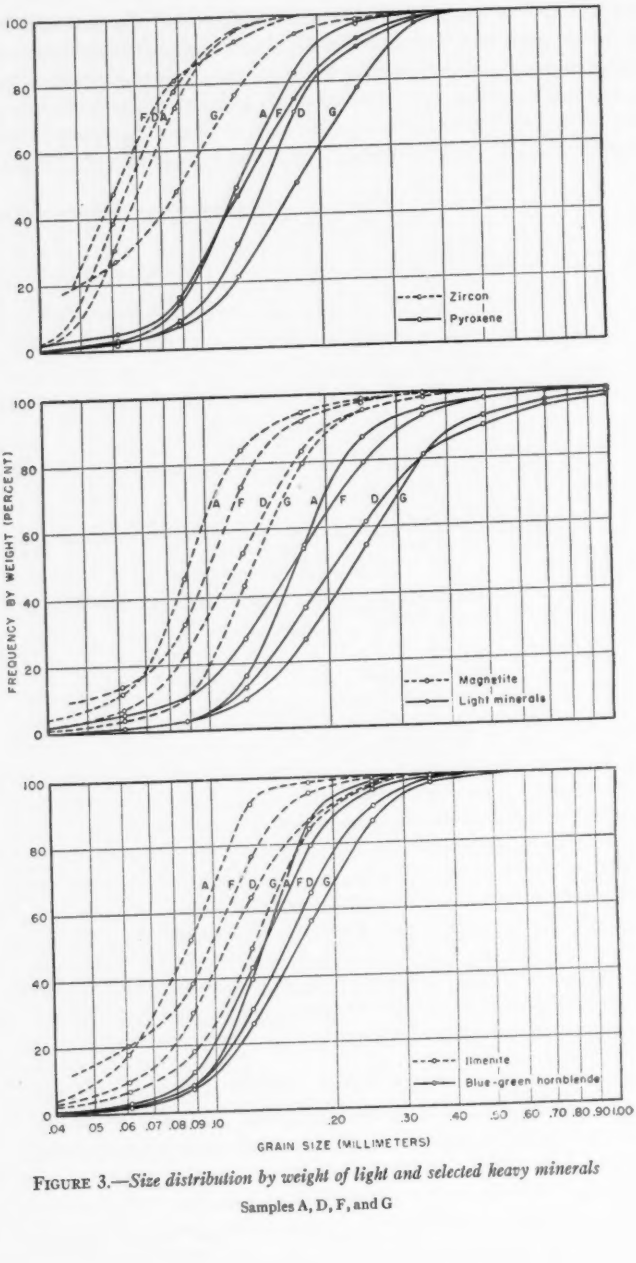

FIGURE 3.—*Size distribution by weight of light and selected heavy minerals*

Samples A, D, F, and G

which has the coarsest light minerals, also has the coarsest heavy minerals. Samples A and F, which have the finest light minerals, also have the finest heavies.

Differences in sorting of the light minerals, as exhibited by samples A and F, are accompanied by consistent differences between the size distributions of the various heavy minerals in these two samples. The heavy minerals of sample A, the better sorted of the two samples, are finer than the heavies in sample F. This difference in fineness is greatest for heavies of high specific gravity.

The similarity in relative position of the light and various heavy minerals in the four samples leaves little doubt that the heavy-mineral composition in these sand deposits not only varies with differences in average size and degree of sorting, but that the variations are systematic and should be relatable to some basic law or laws of sediment transportation and deposition. What factors may cause differences in size distribution within a single sample and systematic variations between samples?

FACTORS GOVERNING HEAVY-MINERAL OCCURRENCE

HYDRAULIC EQUIVALENT SIZES IN THE RIO GRANDE

For 50 miles or more above Bosque, New Mexico, no large tributaries contribute sediment directly to the Rio Grande channel. Consequently, as sand moves downstream through this reach of the river, there should be ample opportunity for thorough mixing of the sands brought to the Rio Grande by the tributaries above Albuquerque, New Mexico. The mineral composition of the sediment available for deposition at Bosque, therefore, should be essentially the same at all points across the river. If this is true, then the size distribution of the lights and heavies in the Bosque samples is the result of (1) the difference in hydraulic conditions in different parts of the transverse section at the time of deposition, and (2) the inherent character of the sand available for deposition. At each sampling point, some particular set of hydraulic conditions must have existed during the deposition of the sediment found there. Therefore, the difference in size distribution between minerals in each sample must be attributed to differences in inherent character of the minerals that are available for deposition. At different points in the cross section, the variation would result from both factors.

Sediment particles have a wide range of size, of specific gravity, of shape, and of other physical and chemical properties that affect their behavior under particular hydraulic conditions. Other factors including size being constant, two grains differing in density would not be picked up with the same frequency or bounced and rolled at the same speed. There would, however, be particles of different sizes that would settle or be transported along the bottom at the same rate. Differences in shape or other physical properties naturally would modify this simple postulated relationship between density and size.

This leads to the concept of hydraulic equivalence—namely, that whatever the hydraulic conditions may be that permit the deposition of a grain of particular physical properties, these conditions will also permit deposition of other grains of equivalent hydraulic value.[4] There is no specification in this general statement

[4] The concept of hydraulic equivalence is not original with the writer, having been stated previously in slightly different form by Rubey (1933b) and others.

as to what sizes, shapes, etc., of grains deposited together may be, or that the sizes, shapes, etc., that will be deposited together from suspension will be the same as those deposited from bed load. This concept has a great practical advantage in that the net effect of differences in physical characteristics of various kinds and sizes of grains may be evaluated, without requiring prior evaluation of size, shape, etc., which together determine the hydraulic equivalence for particular grains. The various subfactors can then be evaluated separately, if desired.

Because it is nearly always present and is commonly the most abundant mineral in stream sand, quartz would appear to be the best base to which the hydraulic equivalence of other minerals could be referred. Where quartz is associated with other light minerals of essentially the same specific gravity, however, it is much easier to use the light minerals as a group as the reference basis. This has been done in this investigation. Because sieves commonly have been used and are convenient for sizing sands, the hydraulic equivalence of heavies will be referred to that of the light minerals in terms of size as determined by sieving—*i.e.*, the light and heavy minerals will be of the same "equivalent hydraulic size".

At a given place and time in a stream, not only will there be inherent differences in physical properties between particles of different kinds, but there may also be differences in the availability for deposit of different sizes of each mineral. In addition, at different times or at different places in the stream, the *absolute* availability of any size of grains will vary because of differing hydraulic conditions. Thus, during high flows more and coarser sand will be transported than during low flows. Under varying hydraulic conditions, however, the *relative* availability of grains of any given equivalent hydraulic size should remain the same. If more light minerals are transported as the stream discharge increases, more heavies of hydraulic equivalent size will be transported; if coarser light minerals are transported, coarser heavies should also be transported. If this were not true, then the heavies and lights would not be of the same equivalent hydraulic size.

Similarly, when heavy minerals are deposited, light minerals of equivalent hydraulic size will be deposited in the proportion in which they are available in the stream load. Consequently, the relative availability should be a constant that is common to the stream load and to all deposits from that stream load, regardless of the differences in absolute amounts of the minerals of the same and other sizes that are deposited under the particular hydraulic conditions existing at different places of deposit.

The great difference in heavy-mineral size distribution that may be caused by relative availability is illustrated in Figure 4. The actual size distribution of light minerals in sample A has been used as a base to compute the size distribution of a heavy mineral that is equivalent in hydraulic size to light minerals one $\sqrt{2}$ size grade larger. Curve X assumes equal relative availability in all size grades; curve Y assumes relative availability increasing geometrically toward the finer sizes.

Relative availability may be expressed as a ratio between the amounts of two minerals by number, volume, or weight. The relation by weight, using light minerals throughout as one of the minerals, is easiest to obtain. In consequence, this hydraulic, relative-availability ratio, termed the "hydraulic ratio" for convenience, is

defined in terms of weight. Because the weight of light minerals is great compared to that of most heavies, the ratio is multiplied by 100 to arbitrarily reduce the number of decimal places. Specifically, then, the hydraulic ratio of a mineral is "100 times the weight of that mineral in a known range of sizes, divided by the weight of light minerals of equivalent hydraulic size."

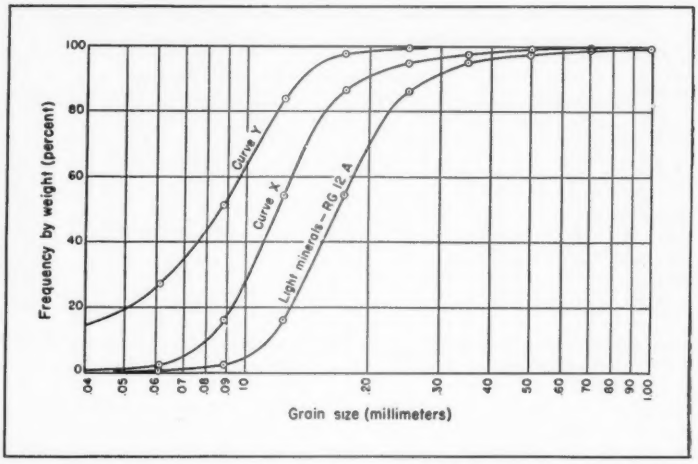

FIGURE 4.—*Hypothetical size distributions of magnetite with difference in relative availability*

Curve *X* assumes equal availability in all size grades, curve *Y* assumes availability increasing geometrically toward the finer sizes.

Three factors that affect the size distributions in the same sample or in samples from a transverse section across a stream may now be summarized: (1) the hydraulic conditions, which vary with time and position and are a composite of many interacting factors, (2) the hydraulic equivalent size, which is also the net effect of several factors, and (3) the relative availability for deposit of the different sizes of each mineral.

At any place in a river, the hydraulic conditions that govern sediment deposition change constantly. Short-time, almost instantaneous, fluctuations will be superimposed on long-time changes in average velocity. The size distributions of light and heavy minerals in the resulting deposit will reflect the net effect of these temporal changes. At any instant, however, all kinds and sizes of mineral grains that are accumulating will be subject to the same hydraulic conditions, whatever they may be. At other instants, this will also be true. Consequently, the differences in size distribution of different minerals in the same sample will be due to the second and third factors. If one factor is known, the other may be computed easily. If neither is known, however, neither can be computed from the size distributions in a single sample.

The size distribution of magnetite in sample A may be used to illustrate this point. It can first to be assumed that light minerals and magnetite of the same size are hy-

draulically equivalent, and the relative availability of various sizes of magnetite necessary to give the actual size distribution of magnetite can be computed. Similar computations can be made, assuming that magnetite grains are hydraulically equivalent to light minerals one, two, or three $\sqrt{2}$ size grades larger. The wide range in apparent relative availability is shown in Table 5. Obviously, if either the

TABLE 5.—*Relative availability of magnetite of various sizes in the stream load*
Computed from sample RG 12A, 1940, for a range of hydraulic equivalent sizes

Size grade	Hydraulic equivalent size (in $\sqrt{2}$ size grades)			
	0	1	2	3
Mm.				
>.351	0.04	0.21	0.51	0.18
.351–.250	.06	.51	.82	.63
.250–.175	.04	.39	1.01	.50
.175–.124	.10	.34	1.08	.87
.124–.088*	1.00	1.00	1.00	1.00
.088–.061	7.11	2.44	.76	.23
<.061	7.26	4.89	.59	.04

* For each hydraulic equivalent size postulated, the .124–.088 mm. size grade was used as a base to show the relative availability in the other size grades.

hydraulic equivalent size or the relative availability were known, it would be easy to compute the other.

In the transverse section of a stream, however, the relative availability for deposit of each size of each mineral theoretically should not vary greatly from place to place. Such other physical characteristics as specific gravity, shape, and roundness that determine the hydraulic value of the sediment particles should also be the same in different parts of the cross section. If both relative availability and equivalent hydraulic size are constant or essentially constant in a cross section, then the two factors can be determined simultaneously by comparing the mineral composition of several samples from different parts of the cross section. The process is similar, in general, to that in mathematics by which two equations are used to solve for two unknowns.

It is not known, however, that the hydraulic equivalent size would be the same for both large and small grains. In fact, it seems probable from theoretical considerations that the opposite would be true. For grains settling through a liquid, as from suspension, fine sand particles presumably would follow Stokes law, whereas coarse sand particles would not (Rubey, 1933a). Thus computation of the hydraulic equivalent size for all size grades at the same time would yield an average value that would be applicable to the entire sample as a whole but not to any particular size of sand. Therefore, single size grades or even smaller units should be compared. Notable differences in hydraulic equivalent size for coarse and fine grains will be shown by differences in the values computed for the different size grades or smaller units.

In actual practice, it is impossible to compute the hydraulic equivalent size for a single size—for example, for grains exactly .088 mm. in diameter. A range of sizes, from .124–.088 mm. diameter, for example, must be used. Since the weight of each

kind of heavy mineral in each size grade is known (Table 4), size grades offer the most convenient subdivision of the samples for computing hydraulic equivalent sizes.

The procedure is as follows: The size-distribution curves of the light minerals of the six samples were plotted as large-scale cumulative curves, the relative boundaries

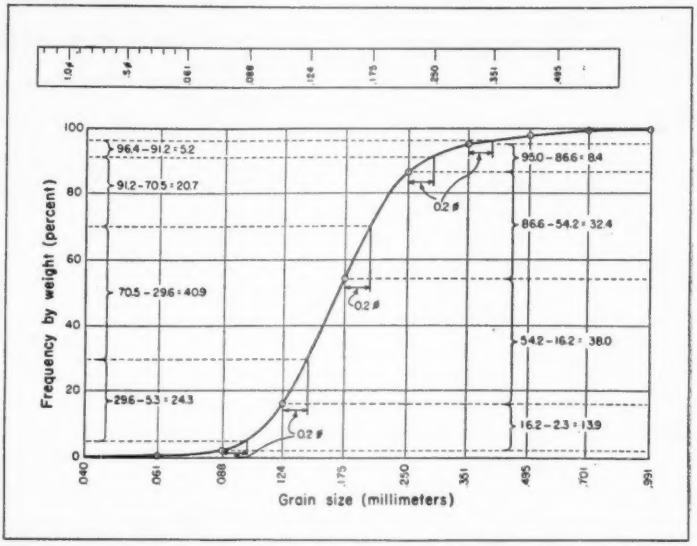

FIGURE 5.—*Diagram illustrating method of obtaining equivalent hydraulic percentages of a sample that are equivalent in hydraulic value to heavy minerals 0.2ϕ smaller*

Size grade boundaries are not those obtained by microprojection calibration

of the size grades being those determined by microprojection (Rittenhouse, 1942). For each size grade of each sample the percentage of light minerals, 0.0, 0.1, 0.2 . . . 1.0ϕ units[5] larger were read from the curves. Figure 5 illustrates this procedure. These percentages were multiplied by the total weight of light minerals in the test samples to give the weight of light minerals 0.0, 0.1, 0.2 . . . 1.0ϕ units larger than the heavy minerals of that size grade.

For each size grade of the six samples, the weight of each heavy mineral was divided by the weight of light minerals of the same size, then by the weight of light minerals 0.1ϕ larger, then by the weight of light minerals 0.2ϕ larger, etc. In this way,

[5] Krumbein (1936) originally suggested the use of a ϕ grade scale to simplify the computation of the moment measures of sediment distributions. In the ϕ scale, the unequal class intervals characteristic of geometric grade scales are eliminated by defining the class intervals in terms of their negative logarithms to the base 2. Thus, the interval between 1.0 and .5 mm. is 1ϕ, and the interval between .5 and .25 is also 1ϕ. For any $\sqrt{2}$ size grade, ϕ is 0.5. Since, in the ϕ notation any interval, such as 0.1ϕ or 0.3ϕ, is the same regardless of the absolute size of the material being compared, it is extremely convenient and useful for designating hydraulic equivalent size. For example, the statement that light minerals from .142–.102 mm. in diameter are equivalent hydraulically to hornblende from .124–.088 mm. in diameter and that light minerals from .201–.142 mm. in diameter are equivalent hydraulically to hornblende from .175–.124 mm. in diameter does not indicate immediately whether the hydraulic equivalent size for the coarser sand is smaller, larger, or the same as that for the finer sand. The statement that the hydraulic equivalent size is 0.2ϕ for both the .124–.088 and .175–.124 mm. size grades of the heavy does have an obvious significance.

hydraulic ratios (relative availabilities) were computed for a wide range of possible hydraulic equivalent sizes. Such a range of hydraulic ratios for ilmenite in samples A, D, F, and G is presented in Table 6.

If both the availability and the physical characteristics of ilmenite were the same at the points where samples A, D, F, and G were deposited, the hydraulic ratios should

TABLE 6.—*Hydraulic ratios for ilmenite in samples A, D, F, and G at Bosque, N. M. (RG 12)*
Computed for a range of hydraulic equivalent sizes

Sample or derived factor	Hydraulic equivalent size														
	.0ϕ	.1ϕ	.2ϕ	.3ϕ	.4ϕ	.5ϕ	.6ϕ	.7ϕ	.8ϕ	.9ϕ	1.0ϕ	1.1ϕ	1.2ϕ	1.3ϕ	1.4ϕ
A	3.4	2.0	1.14	0.77	0.56	0.54	0.54	0.54	0.54	0.54	0.55	0.70	1.05	1.54	2.1
D	2.2	1.8	1.15	.86	.69	.59	.57	.57	.56	.56	.57	.57	.62	.67	.7
F	1.5	1.1	.86	.72	.65	.65	.65	.65	.65	.65	.65	.70	.79	.95	1.1
G	3.7	2.7	2.06	1.57	1.17	1.05	.90	.76	.66	.59	.57	.56	.56	.58	.6
Mean	2.7	1.9	1.30	.98	.77	.71	.67	.63	.60	.59	.59	.63	.75	.93	1.1
Standard deviation	1.0	.7	.53	.40	.27	.23	.16	.10	.06	.05	.04	.08	.22	.42	.7
Coefficient of variation	38.	35.	41.	40.	36.	33.	24.	16.	10.	8.1	7.6	12.	29.	45.	61.

be exactly the same for one of the postulated hydraulic equivalent sizes in Table 6. For both low and high hydraulic equivalent sizes there is a wide variation in the hydraulic ratios of the four samples. In the center of the range, however, the agreement is good but not perfect. This is shown very well in Figure 6, in which the hydraulic ratios have been plotted against hydraulic equivalent size.

The coefficient of variation (standard deviation/arithmetic mean) provides a measure of the similarity between the hydraulic ratios in the four samples. The coefficient of variation for each hydraulic equivalent size of ilmenite is also presented in Table 6 and in graphic form in Figure 6. The lowest value is 7.6 per cent and occurs at 1.0ϕ. At higher values the coefficient of variation increases rapidly but at lower values the rate of increase is slow. The experimental results thus do not give an exact hydraulic equivalent size for ilmenite, but they certainly do indicate that it is probably between 0.8ϕ and 1.1ϕ, a fairly narrow range. Thus, for ilmenite of this size the probable range can be given as 0.8–1.1ϕ, and the best value as 1.0ϕ. In other words, ilmenite apparently is transported and deposited with light minerals about one Wentworth or two $\sqrt{2}$ size grades larger.

Similar computations, using the data from all 6 Bosque samples, were made for 4 size grades of ilmenite and 15 other heavy minerals. The best values are presented in the first four figure columns of Table 7. For convenience, the minerals have been listed in order of decreasing specific gravity. It will be noted that, in general, high specific gravity is accompanied by large hydraulic equivalent size, and low density by low hydraulic equivalent size. Of particular interest is zircon, which is notably finer in size than any of the other heavies (Table 4; Fig. 3) but has a hydraulic equivalent size in line with its specific gravity. Deficiency of coarse zircons is the explanation of this apparent discrepancy.

Three suites of suspended-load samples collected at Escondido, New Mexico, dur-

ing the flood of June and July 1941 also provide information on hydraulic equivalent sizes. These samples were obtained from different parts of the transverse cross section and at different water depths. In the laboratory they were sieved, and the mineral composition of two or three size grades of each sample determined in the

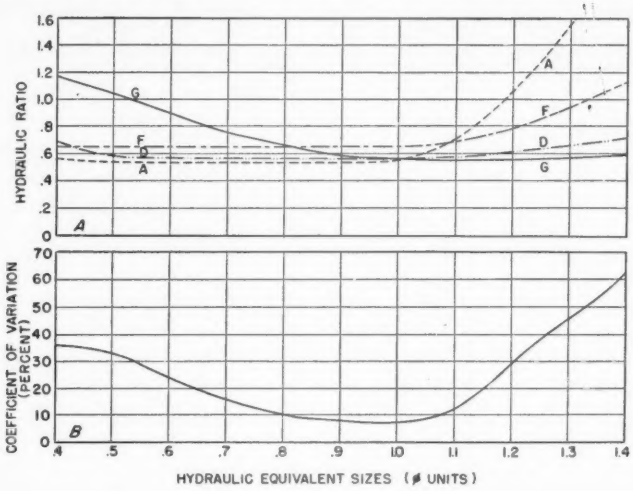

FIGURE 6.—*Hydraulic ratios and coefficient of variation*

A, Hydraulic ratios for ilmenite in samples A, D, F, and G, computed for a range of hydraulic equivalent sizes. *B*, Coefficient of variation for hydraulic ratios in the same samples, computed for the same range of hydraulic equivalent sizes.

same manner as for the Bosque samples. For each size grade hydraulic ratios were computed for a range of hydraulic equivalent sizes from 0.0ϕ to 1.0ϕ. Coefficients of variation were computed for all samples for enough 0.1ϕ units of the possible range to indicate the best value of the hydraulic equivalent size. These best values are presented in columns five and six of Table 7. This transit load data will be reported and analyzed in detail at a later date.

In general, the hydraulic equivalent sizes, as determined from the transit samples at Escondido, agree very well with those determined from the bed deposits at Bosque. Such agreement between values obtained by independent investigation of two different kinds of samples from widely separated points on the same stream indicates that the concept of hydraulic equivalence is a good one—*i.e.*, that on the average light minerals are transported and deposited with heavy minerals of a different size.

MAGNITUDE OF UNEXPLAINED VARIATIONS

In determining equivalent hydraulic size, the phi (ϕ) value at which the coefficient of variation was smallest was considered to be the true hydraulic equivalent size. Even at the best ϕ value, however, there remained some unexplained variation. For the example in Table 6, this was 7.6 per cent. For all other minerals studied, these unexplained variations, expressed as coefficients of variation of the hydraulic

ratios (C_{hr}), are presented in the second figure column under each of the four size grades in Table 8.

To some unknown degree, these variations are caused by chance errors of sampling; the remainder, if any, represents variation due to some unknown factor or factors.

TABLE 7.—*Hydraulic equivalent sizes of various heavy minerals*

As determined from bed samples from Bosque and transit samples at Escondido, New Mexico

Mineral	Specific gravity	Bed samples (Bosque)				Transit samples (Escondido)		Best value all sizes
		Size Grade						
		.250–.175 mm.	.175–.124 mm.	.124–.088 mm.	.088–.061 mm.	.175–.124 mm.	.124–.088 mm.	
		φ units	*φ units*	*φ units*	*φ units*	*φ units*	*φ units*	*φ units*
Magnetite	5.2	.9	1.2	1.0	1.0	1.1	1.0	1.0
Ilmenite	4.7	.8	1.0	.9	1.0	1.1	.9	1.0
Zircon	4.6	.....	.8	.9	.9	.....	.....	.9
Barite	4.5	.6	.4	.7	.2	.....	.....	.5
Garnet	3.8	.8	.8	.3	.6	.5	.8	.6
Kyanite	3.6	.3	.5	.0	.....	.....	.....	.3
Titanite	3.5	.7	.4	.7	.3	.3	.7	.5
Pyroxene	3.4	.4	.7	.1	.3	.3	.3	.3
Hypersthene	3.4	.5	.3	.4	.2	.3	.3	.4
Diopside (Br)	3.4	.5	.2	.1	.5	.....	.....	.3
Diopside (C)	3.3	.3	.4	.6	.4	.....	.....	.4
Blue-green hornblende	3.2	.2	.0	.0	.1	.3	.3	.2
Green hornblende	3.2	.4	.1	.1	.2	.4	.2	.2
Brown hornblende	3.2	.3	.2	.0	.0	.3	.2	.2
Apatite	3.2	.6	.5	.2	.4	.4	.4	.4
Tourmaline	3.1	.0	.0	.3	.1	.3	.4	.2

Consequently, if the errors due to sampling are determined and compared with the total unexplained variations, the remaining unexplained variation, if any, will measure the extent to which factors, other than hydraulic conditions, hydraulic equivalent size, and relative availability govern the entrainment, transportation, and deposition of heavy minerals. In making the comparisons, the actual variations in hydraulic ratios for the average best value (column 7, Table 7) rather than the best values determined for individual size grades will be used.

The sampling errors of hydraulic ratios could not be predicted directly from any statistical equation known to the writer. Additional experimental work (Rittenhouse and Bertholf, 1942), however, showed that an equation, similar to that used by Dryden (1935) to predict the sampling errors of number frequencies, could also be used to predict the sampling errors of hydraulic ratios. The procedure was as follows: Eight splits were made from a composite sample, and the size distribution of each determined by sieving. The sand in the .124–.088 mm. size grade of each sample was split in two parts and the parts weighed. The heavies and lights were separated from one part by gravity settling, from the other part by centrifuge. After washing, drying, and weighing, the magnetite was removed and weighed. A random split of

each of the 16 nonmagnetic fractions was mounted, and the mineral frequencies by number in each obtained by identifying 325 to 380 randomly selected grains.

The variation in number frequency of each mineral was computed for the eight gravity and the eight centrifuge fractions separately. These coefficients of variation were plotted against the percentages by number on logarithmic paper (Fig. 7).

TABLE 8.—*Mineralogical analysis, coefficients of variation*

(In per cent)

Mineral	Specific gravity	Size Grade											
		.250–.175 mm.			.175–.124 mm.			.124–.088 mm.			.088–.061 mm.		
		C_s*	C_{hr}†	C_w**	C_s	C_{hr}	C_w	C_s	C_{hr}	C_w	C_s	C_{hr}	C_w
Ilmenite	4.7	16.	62.	98.	10.	53.	103.	5.	23.	48.	4.	20.	67.
Zircon	4.6	.....	.....	.....	57.	64.	82.	25.	44.	49.	12.	24.	58.
Barite	4.5	104.	83.	108.	70.	57.	58.	37.	58.	58.	30.	34.	32.
Garnet	3.8	41.	80.	143.	24.	59.	81.	22.	40.	29.	22.	17.	56.
Kyanite	3.6	79.	21.	35.	57.	48.	46.	49.	74.	55.	.....	.....	.....
Titanite	3.5	49.	28.	65.	33.	28.	31.	25.	31.	35.	28.	50.	40.
Pyroxene	3.4	15.	13.	30.	13.	24.	28.	12.	14.	13.	15.	22.	35.
Hypersthene	3.4	28.	48.	68.	26.	20.	22.	22.	40.	58.	25.	40.	43.
Diopside (Br)	3.4	48.	74.	91.	31.	52.	51.	33.	65.	53.	36.	60.	47.
Diopside (C)	3.3	42.	32.	44.	31.	37.	43.	25.	34.	33.	30.	29.	44.
Blue-green hornblende	3.2	15.	38.	39.	11.	14.	11.	10.	21.	11.	15.	12.	18.
Green hornblende	3.2	22.	36.	45.	18.	19.	20.	14.	21.	24.	15.	6.	20.
Brown hornblende	3.2	48.	60.	56.	30.	28.	31.	23.	25.	19.	23.	28.	29.
Apatite	3.2	60.	71.	69.	34.	31.	42.	22.	21.	28.	21.	24.	35.
Tourmaline	3.1	70.	86.	73.	31.	46.	42.	23.	13.	22.	22.	25.	29.
Magnetite	5.2	.....	29.	67.	.....	39.	86.	.....	23.	47.	.....	32.	54.

* Coefficient of variation (theoretical) based on number of grains counted and frequency by number of each mineral species.

† Total coefficient of variation based on hydraulic ratios.

** Total coefficient of variation based on weight percentages.

For any mineral the sampling error (in number frequency) may be computed from the equation $C_s = \sqrt{npq}/np$, in which C is the coefficient of variation, n is the total number of grains counted, p is the number frequency of the mineral, and q is the sum of the number frequencies of all other minerals. For any n, the C for different values of p may be computed and a curve drawn to show the change in C with change in p. This was done separately for the average n of the eight gravity and the eight centrifuge samples. It was found that these curves fitted the points obtained experimentally from the gravity and centrifuge samples (Fig. 7). This was not unexpected, since chi-square tests of the same data (*see* section on Percentages by Number) showed the variation to be well within the limits to be expected in sampling. A similar close agreement between experimental points and theoretical values has been obtained for beach sands (Krumbein and Rasmussen, 1941). This means that error of reduction in sample size is so much larger than other laboratory errors that they may be neglected.[6]

Next, the number percentages were converted to weight per cent, the weights of

[6] Independent errors (c_1, c_2, etc.) are related to the total error (C) by the equation $C = \sqrt{c_1^2 + c_2^2}$ (Krumbein and Pettijohn, 1938, p. 266). Thus if one suberror is essentially the same as the total error, the other suberrors must be relatively small.

each heavy mineral were computed, and the hydraulic equivalent weights obtained graphically. From these the hydraulic ratios in the eight gravity and eight centrifuge samples were calculated. For each mineral the coefficient of variation of these hydraulic ratios was determined. It was found that the coefficients of variation of

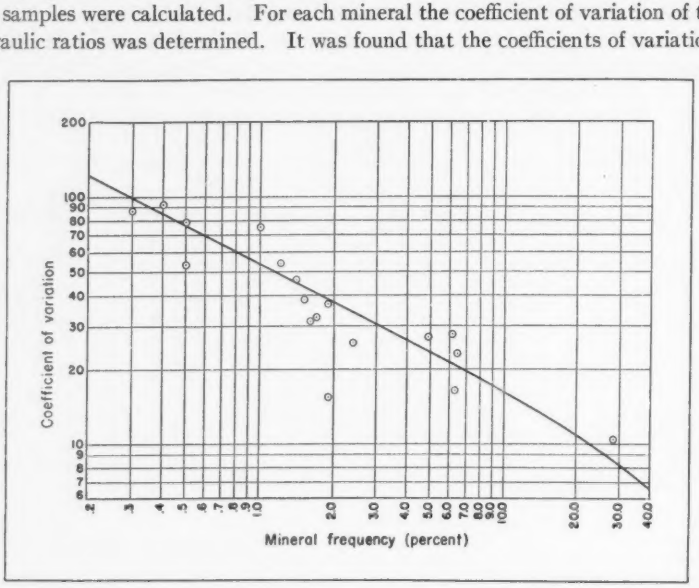

FIGURE 7.—*Experimentally determined and theoretical coefficients of variation of number frequencies*
Determined for the gravity separates of sample RG 8, 1938

the hydraulic ratios were essentially the same as the coefficients of variation of the percentages by number. Therefore, if the coefficient of variation is obtained for any mineral from (1) the total number of grains counted, and (2) the percentage by number, using the equation $C_s = \sqrt{npq}/np$, this coefficient of variation is also the coefficient of variation for the hydraulic ratio of that mineral. This is important since it provides a means by which the sampling errors of hydraulic ratios may be determined for any sample and permits tests of significance to be made between samples.

Coefficients of variation (C_s) so obtained may be compared with those (C_{hr}) obtained from the six Bosque samples, to determine the extent of unexplained variation In Table 8, the sampling variations are in the first column, and the experimentally determined variations are in the second column under each size grade.

For some minerals in each size grade C_{hr} is larger than C_s; for others the reverse is true. Thus, for 41 of the 58 comparisons (71 per cent), C_{hr} exceeds C_s; for 17, C_s exceeds C_{hr}. For the high-density minerals—ilmenite, zircon, barite, and garnet—the C_{hr} is greater for 12 of the 15 comparisons (80 per cent). For the minerals of low density, the C_{hr} is greater for 29 of 43 comparisons (67 per cent).

In interpreting these results, it must be remembered that the C_{hr} values are determined experimentally and consequently would be expected to scatter about any values derived from theoretical curves. Such scattering was well shown in the gravity and centrifuge experimental data (Fig. 7). About half the values would be

expected to be larger and half smaller than those determined theoretically. Some deviation from this 50–50 ratio would be expected, but how much is not known. For the gravity samples the ratio was exactly 50–50; for the centrifuge samples it was 70–30, with most points being smaller than the theoretical; and for Krumbein and Rasmussen's data (1941) it was about 43–57.

TABLE 9.—*Percentage by which the coefficients of variation of hydraulic ratio (C_{hr}) and weight percentage (C_w) exceed the coefficient of variation of random sampling (C_s)*

(In per cent)

Kind of heavy minerals	Size Grade								Average of all size grades	
	.250–.175 mm.		.175–.124 mm.		.124–.088 mm.		.088–.061 mm.			
	C_{hr}	C_w	C_{hr}	C_w	C_{hr}	C_w	C_{hr}	C_w	C_{hr}	C_w
High density	94.*	255.*	141.	298.	144.	261.	121.	530.	127.	341.
Low density	1.	49.	15.	22.	36.	36.	13.	50.	16.	39.
All	20.	93.	49.	96.	64.	96.	43.	187.	45.	117.

* If C_s were 10 per cent, C_{hr} would be 19.4 per cent, and C_w would be 35.5 per cent.

For high-density heavies it appears unlikely that the deviations are due to chance. Not only are 80 per cent of the actual values larger than the theoretical, but many of them are several times as large. For ilmenite—the outstanding example—C_{hr} in each of the four sizes grades is more than four times as large as C_s. Apparently some factor or factors in addition to the three that were postulated affect the transportation and deposition of high-density heavies.

Although the deviations for low-density heavies might be due to chance, it seems more probable that there is some unexplained variation in excess of that to be expected as a result of sampling. If this is true, some factor or factors in addition to the three that were postulated also affect the transportation and deposition of heavies of low density, but to a lesser degree than they do high-density heavies.

From the Bosque data the importance of these additional unknown factors may be approximated.[7] Average percentages by which C_{hr} exceeds C_s are presented in the first figure column under each size grade in Table 9. For high-density heavies (ilmenite, zircon, barite, and garnet), the average C_{hr} was found to exceed C_s by 127 per cent. The range for individual size grades was from 94 to 144 per cent. For low-density heavies, the average C_{hr} exceeds C_s by only 16 per cent, ranging from 1 to 36 per cent in the individual size grades. If C_s of a high-density mineral were 20 per cent, for example, C_{hr} would be about 45 per cent (20×2.27); for a low-density mineral, C_{hr} would be 23 per cent (20×1.16). The increase of 25 and 3 per cent respectively for the high- and low-density minerals in this example represents the influence of a factor or factors other than the three outlined—*i.e.*, (1) hydraulic conditions, (2) hydraulic equivalent size, and (3) relative availability.

[7] For each mineral in each size grade C_{hr} was divided by C_s, or C_s divided by C_{hr}, the smaller value in each case being used as the divisor. (When C_{hr} is less than C_s, the ratio C_{hr}/C_s may vary from 1 to 0, but when C_{hr} is greater than C_s, the ratio C_{hr}/C_s may vary from 1 to ∞. Consequently, if the same factor were used throughout as the divisor, any average of a number of ratios would be too large.) The C_{hr}/C_s quotients were considered positive, and the C_s/C_{hr} quotients negative. Then $100\ (C_{hr}/C_s) - 100$ and $100\ (C_s/C_{hr}) + 100$ represent the percentages by which the larger variation exceeds the smaller. These percentages were summed by individual size grades and for all size grades together. Such sums were obtained for heavies of high density, for heavies of low density, and for all heavies. The sums were divided by the number of items in each to give an average percentage by which C_{hr} exceeds C_s.

The average C_s is dependent on the total number of grains counted in the nonmagnetic fraction. The average percentages (127 and 16) by which C_{hr} exceeds C_s were determined for a C_s based on an average count of 780 grains. If more or less grains were counted, C_s would decrease or increase, and the 127 and 16 per cent values

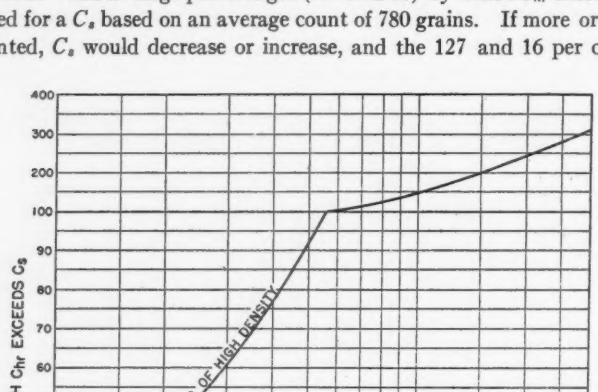

FIGURE 8.—*Percentage by which C_{hr} exceeds C_s* (780 grain count)
For counts of from 100 to 3000 grains

would no longer be applicable. Since the unexplained variations are independent of C_s, however, they may be evaluated from the equation $C_x = \sqrt{C_{hr}^2 - C_s^2}$, in which C_x is the average magnitude of the unexplained variations. These C_x values are presented in the first figure column under each size grade in Table 10. These C_x values are fixed and unlike the average excess percentages (Table 9) are independent of C_s, though they are presented in terms of percentages of a C_s from a 780 grain count. For high-density heavies, C_x is 204 per cent of the C_s for a 780 grain count; for low-density heavies it is 58 per cent.

With C_x evaluated, the C_{hr} for any mineral with any grain count can be estimated from the equation $C_{hr} = \sqrt{C_s^2 + C_x^2}$, in which C_s is based on the new grain count, and $C_x = 2.04$ [C_s (780 grain count)] for minerals of high density or $C_x = .58$ [C_s (780 grain count)] for minerals of low density. From this equation it may be seen that the relative importance of C_x in determining C_{hr} becomes smaller as C_s increases. Thus, for a count of 300 grains, a count commonly used in heavy mineral investigations, the average percentage by which C_{hr} would exceed C_s is about 61 per

cent for high-density heavies and 6 per cent for low-density heavies. For counts of 100 to 3000 grains, the average percentage by which C_{hr} exceeds C_s (based on the C_x from the Bosque data) can be determined graphically for both high- and low-density heavies from Figure 8.

What are the factors that cause the unexplained variations? There are several possibilities, the relative importance of which are not known. First, in the Rio Grande some sand is transported in suspension, some by traction. The hydraulic equivalent sizes for these two modes of transportation may not be the same. If not, the hydraulic equivalent sizes that were determined experimentally from the Bosque samples represent some intermediate average hydraulic equivalent size for the cross section as a whole. But if the proportion of suspended and traction load was not the same in the six samples studied, some variation in the hydraulic ratios would result. Further studies in other streams, or under controlled conditions in flumes, should provide evidence on this point.

It is also possible that some variation in relative availability from place to place in the cross section may have resulted from inadequate mixing of the sand as it was transported down the Rio Grande. Although no major tributaries enter the Rio Grande for about 50 miles upstream, a relatively small tributary nearer Bosque might, under exceptional conditions, have contributed enough sediment to modify the mineral composition slightly.

Also, the variations for heavy minerals of low density might conceivably be due to errors of random sampling. It seems less probable, however, that the unexplained variations for heavies of high density could be due to sampling. Further investigations should indicate more accurately the effect of sampling errors.

VARYING HYDRAULIC CONDITIONS

To what extent do varying hydraulic conditions at different times or places affect heavy-mineral size distributions at a transverse cross section? Obviously, if the effect is minor, the additional time and effort involved in eliminating or reducing it is largely wasted. Weight percentages of heavy minerals in a size grade—*i.e.*, the weight of a heavy mineral divided by the weight of sediment of the same absolute size—should not eliminate the effect of varying hydraulic conditions. Consequently, a comparison of (1) the coefficients of variation of weight percentages (C_w), hydraulic ratios (C_{hr}), and the theoretical sampling errors (C_s), and (2) the mean weight percentages and hydraulic ratios will indicate the magnitude of effects due to varying hydraulic conditions.

Weight percentages were determined for each mineral in four size grades of the Bosque samples. The C_w values were computed and are presented in the third figure column under each size grade of Table 8. In 50 of the 58 comparisons (86 per cent) C_w exceeds C_s, in 1 they are the same, and in 7 C_s exceeds C_w. For high-density heavies, C_w exceeds C_s in 14 of 15 comparisons. For low-density heavies, C_w exceeds C_s in 36 of 43 comparisons (84 per cent). For both low- and high-density heavies, C_w exceeds C_s more times than C_{hr} exceeds C_s.

The average percentage by which C_w exceeds C_s was computed for each of the four size grades and for all size grades together. These percentages are presented in the

second figure column under each size grade in Table 9. Except for low-density heavies in the .124–.088 mm. size grade, the average C_w values exceed the average C_{hr} values, in many cases being more than twice as large.

Since the variations caused by varying hydraulic conditions (C_y) are independent of those due to sampling and to other unexplained factors, they may be evaluated

TABLE 10.—*Errors due to unexplained factors (C_x) and varying hydraulic conditions (C_y) in terms of the coefficient of variation of random sampling (C_s) for a 780 grain count*

(In per cent)

Kinds of heavy minerals	Size Grade								Average of all size grades	
	.250–.175 mm.		.175–.124 mm.		.124–.088 mm.		.088–.061 mm.			
	C_x	C_y	C_x	C_y	C_x	C_y	C_x	C_y	C_x	C_y
High density	1.66*	2.97*	2.19	3.16	2.22	2.66	1.97	5.90	2.04	3.78
Low density	.14	1.09	.57	.41	.92	.00	.53	.99	.58	.77
All	.66	1.51	1.11	1.27	1 30	1.07	1.02	2.48	1.05	1.61

* If C_s were 10 per cent, C_x would be 16.6 per cent, C_y would be 29.7 per cent. Also $C_{hr} = \sqrt{C_s^2 + C_x^2} = 19.4$ per cent, and $C_w = \sqrt{C_s^2 + C_x^2 + C_y^2} = 35.5$ per cent.

from the equation $C_y = \sqrt{C_w^2 - C_s^2 - C_x^2}$. These C_y values, presented in the second figure column under each size grade in Table 10, are comparable to the C_x values in the same table. Variations due to hydraulic conditions, particularly for high-density minerals, are large and, therefore, well worth spending time and effort to eliminate. C_y may be expected to increase as the range in average size and degree of sorting of the light minerals increase, and to decrease relative to C_s as the number of grains counted is decreased. The C_y values determined from the Bosque data cannot be applied to other investigations in which the range and magnitude of hydraulic conditions are different.

Whatever C_x and C_y may be at any locality, they may be reduced, theoretically at least, by collecting two or more spot samples and combining them into a single composite sample. Such reduction would be inversely proportional to the square of the number of spot samples combined into the composite. This relationship would appear to hold, at least approximately, provided two important qualifications are made. First, if three spot samples are combined, the expected reduction in C_x and C_y will occur only for those size grades common to all three samples. There will be partial reduction in size grades common to two of them, and no reduction in the other size grades. Similarly, if some samples contribute more sediment than others to any size grade of the composite, the reduction in C_x and C_y will not be inversely proportional to the square of the number of samples but will depend on the relative amounts of sediment contributed by each. Second, the smaller C_y values obtained from composite samples will not apply to other sands that were deposited under a different range or magnitude of hydraulic conditions. Before C_y of a series of composite samples may be determined, the entire range and magnitude of hydraulic conditions under which all samples were deposited must be considered.

The C_w and C_y values measure the variation about the mean weight percentages. If weight percentages rather than hydraulic ratios are used to represent heavy-

mineral compositions, however, the absolute mean value as well as the variation about the mean must be considered. Depending on the relative position of the size grade being studied to the size distribution of the light minerals, and on the hydraulic equivalent size of the heavy mineral, the weight percentages will be smaller or larger than the hydraulic ratios.

TABLE 11.—*Weight percentages and hydraulic ratios for various minerals in four size grades of the Bosque bed samples*

Mineral	Size Grade							
	.250–.175 mm.		.175–.124 mm.		.124–.088 mm.		.088–.061 mm.	
	Hydraulic ratio	Weight percentage	Hydraulic ratio	Weight percentage	Hydraulic ratio	Weight percentage	Hydraulic ratio	Weight percentage
Magnetite	.59	.15	.56	.48	.66	1.57	.41	3.80
Ilmenite	.34	.10	.41	.37	.58	1.40	.38	3.80
Zircon	.....	.....	.012	.011	.031	.074	.062	.56
Barite	.004	.003	.005	.006	.016	.031	.021	.096
Garnet	.019	.011	.029	.036	.038	.076	.024	.13
Kyanite	.003	.003	.007	.008	.008	.013	.....	.....
Titanite	.010	.007	.020	.023	.027	.052	.019	.086
Pyroxene	.073	.063	.101	.117	.114	.185	.101	.295
Hypersthene	.028	.022	.029	.033	.034	.066	.029	.107
Diopside (Br)	.010	.008	.022	.024	.018	.032	.013	.048
Diopside (C)	.011	.009	.019	.025	.030	.048	.023	.068
Blue-green hornblende	.070	.065	.132	.146	.172	.243	.135	.278
Green hornblende	.033	.030	.056	.064	.101	.146	.122	.253
Brown hornblende	.007	.007	.022	.025	.037	.053	.053	.110
Apatite	.005	.006	.016	.020	.034	.063	.044	.169
Tourmaline	.004	.004	.018	.020	.038	.056	.065	.131

This is well illustrated by Table 11, in which the average hydraulic ratios and the average weight percentages are given for four size grades of the Bosque samples. For the coarsest size grade, the weight percentages average about two thirds as large as the hydraulic ratios; for the .175–.124 mm. size grade, they are slightly larger for minerals of low density and smaller for minerals of high density; for the .124–.088 mm. size grade, they average about twice as large; and for the .088–.061 mm. size grade, they are about five times as large. In general, the minerals of low density show less difference then minerals of high density. This relationship would be expected to hold for other localities, though the particular size grades of best agreement would vary with the average texture of the deposit.

The difference in absolute value between hydraulic ratios and weight percentages will not be important if the size distribution of the light minerals is the same in all samples being compared, since the weight percentages will be in error the same relative amount in all of them. If the size distribution varies, however, quite misleading conclusions may be reached.

A common type of detailed heavy-mineral study, for example, is that in which the change in mineral composition is related to the distance of transport. If the average size of the deposits decreases with increasing distance from the source as is commonly

the case, weight percentages may indicate trends that actually do not exist. This is shown in Figure 9A, in which the relative availabilities of magnetite and pyroxene actually remain the same in a series of samples, but the weight percentages change. The increase in weight percentage is greater for magnetite than for pyroxene, which

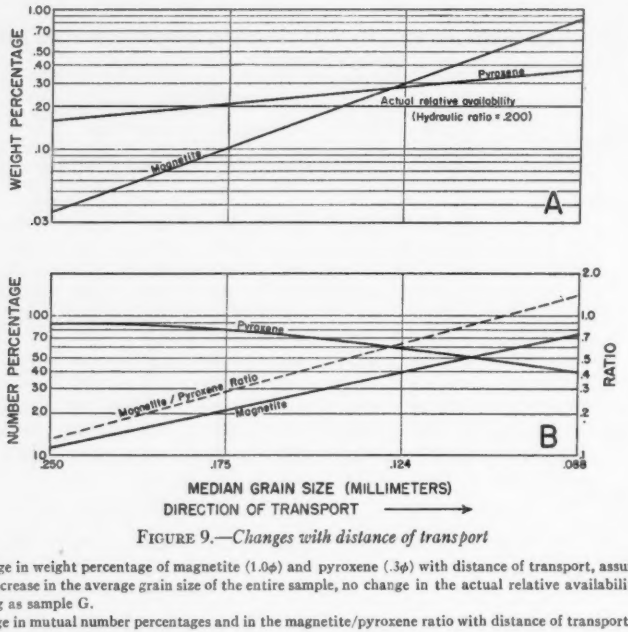

FIGURE 9.—*Changes with distance of transport*

A, Change in weight percentage of magnetite (1.0ϕ) and pyroxene (.3ϕ) with distance of transport, assuming an exponential decrease in the average grain size of the entire sample, no change in the actual relative availability, and the same sorting as sample G.

B, Change in mutual number percentages and in the magnetite/pyroxene ratio with distance of transport. Assumptions are the same as for *A*.

is of smaller hydraulic equivalent size. In Figure 9B, the same data have been presented as mutual number percentages of magnetite and pyroxene and as a ratio between magnetite and pyroxene. Several misinterpretations of the genetic significance of these number percentage and ratio data are possible.

When the size distributions of light minerals are plotted as cumulative curves on semilogarithmic paper, the central part of the curve, extending from about 25 to 75 per cent by weight, is relatively straight. For size grades located within this straight section, the weights of light minerals that are of the same absolute size and the same hydraulic size as the heavies will not differ greatly. For the .175–.124 mm. size grade in Figure 5, for example, the values are 38.0 and 40.9 per cent, and, consequently, the weight percentages and hydraulic ratios will be essentially the same. In contrast, for size grades in the curved sections, the absolute size and equivalent hydraulic size of light minerals will contain quite different weights of light minerals, and the weight percentages and hydraulic ratios will differ materially. For the .124–.088 mm. size grade in Figure 5, for example, the values are 13.9 and 24.3 per cent. The weight percentages would be almost twice the hydraulic ratios.

In considering weight percentages in samples of differing average size or sorting, it would be expected that those size grades located on or near any straight sections that are common to all samples would have weight percentages most nearly equal to the hydraulic ratios and would also show lower coefficients of variation between the weight percentages. This is well shown by the Bosque data in Tables 8 and 10 and by Figure 9A. The greater the differences in size distribution, the less chance there will be for straight sections of the curves to be common to all samples, and, consequently, the more need there will be to use hydraulic ratios rather than weight percentages to represent heavy-mineral compositions.

CHANGE IN HYDRAULIC EQUIVALENT SIZE WITH SIZE

In Table 7 there is some indication that the hydraulic equivalent size for the coarser size grades is larger than for the finer size grades. The Bosque samples provide data for further testing of this point. In using size grades to compute hydraulic ratios for a range of possible hydraulic equivalent sizes, it was assumed that the hydraulic equivalent size of light minerals, as expressed in ϕ units, was the same for both the lower and the upper limit of each size grade. For example, it was assumed that if pyroxene .124 mm. in diameter was hydraulically equivalent to light minerals 0.3ϕ larger, then pyroxene .175 mm. in diameter was also hydraulically equivalent to light minerals 0.3ϕ units larger. But, if hydraulic equivalent size increases with grain size, the coarser heavies would actually be hydraulically equivalent to somewhat larger lights—*i.e.*, pyroxene .175 mm. in diameter would be equivalent to light minerals more than 0.3ϕ units larger.

As the range of heavy mineral sizes to be used is reduced below a $\sqrt{2}$ sieve interval, the difference in size of light minerals that would be hydraulically equivalent to the smallest and largest heavies would also be reduced. When the range in size of heavies is reduced to zero, the difference in hydraulic equivalent size of light minerals would also be zero.

From the cumulative size-distribution curves of the heavy minerals, the percentage of heavies or lights may be obtained graphically for any given range of sizes. From these percentages, the weight of heavies in the selected size range is obtained by multiplying the percentage by the total weight of heavies in the sample. As the range is reduced, however, the errors involved in determining the percentages increase. Consequently, there is a practical lower limit to the range sizes that can be used.

In the present study, the range selected was one-fifth of a $\sqrt{2}$ size grade. Since a $\sqrt{2}$ interval is 0.5ϕ units, the selected range was 0.1ϕ unit (0.1 of a Wentworth size grade). The procedure was as follows: The size distributions of selected heavy minerals in samples A, B, C, F, D, and G were plotted as large-scale cumulative curves, using the size grade limits as determined by sieve calibration (Rittenhouse, 1942). Each heavy-mineral curve was then subdivided into 0.1ϕ units and the percent by weight in each 0.1ϕ unit was read from the curves. These weight percentages were multiplied by the total weight of heavy mineral in the sample to give the weight of that heavy mineral in each 0.1ϕ unit of the size distribution. The size distribution of the light minerals in samples A, B, C, D, F, and G were plotted to the same scale and divided into 0.1ϕ units that coincided with those for the heavies. The

percent by weight and the weight of light minerals in each 0.1ϕ unit were thus obtained.

The data are similar in all respects to those used for determining hydraulic equivalent size by size grades, except that the range of sizes for each determination is 0.1ϕ

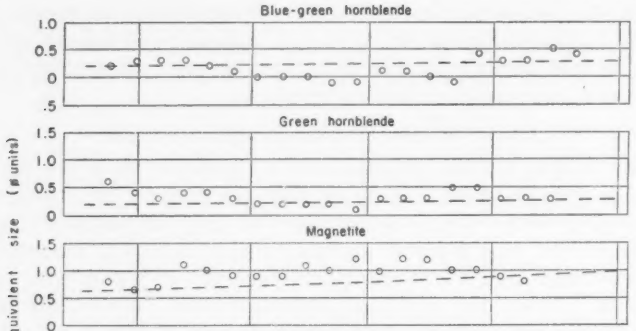

FIGURE 10.—*Relation between grain size and hydraulic equivalent size of selected heavy minerals from samples A, B, C, D, F, and G*

Dashed lines represent settling velocities of spheres having the same specific gravity as the mineral

instead of about 0.5ϕ. Consequently, the procedure in obtaining the hydraulic equivalent size for the new and smaller ranges is essentially the same. The weight of heavy mineral in the same 0.1ϕ unit of each of the six samples was divided first by the weight of light minerals 0.1ϕ larger, then by the weight of light minerals 0.2ϕ larger, etc. In this way hydraulic ratios were computed for a wide range of possible hydraulic equivalent sizes. Coefficients of variation of the hydraulic ratios were obtained for each of the possible hydraulic equivalent sizes, the lowest coefficient of variation in the range representing the least variation in the hydraulic ratios, and, consequently, the best available estimate of the correct hydraulic equivalent size.

Similar computations were made for other 0.1ϕ subdivisions of the heavy-mineral size distribution curves. The best values for each mineral have been plotted in Figure 10. For comparison, hydraulic equivalent sizes, as computed from Rubey's general settling formula for spheres (1933a), are shown by dashed lines in the same figure.

Several facts are apparent from examination of these curves. (1) The curves are

not straight lines, but there is not a progressive increase in hydraulic equivalent size from fine to coarse; (2) the best values for all sizes of each mineral lie within limits of about 0.4ϕ—i.e., for green hornblende between 0.1ϕ and 0.5ϕ, for magnetite between 0.8ϕ and 1.2ϕ, etc.; (3) the heavies of high specific gravity have larger hydraulic equivalent sizes than heavies of low specific gravity; (4) the general shape of the curves is the same for all heavies, but the lowest hydraulic equivalent sizes of the high-density heavies are displaced toward the fine sizes relative to those for heavies of low density; (5) the smallest hydraulic equivalent sizes as determined for the Bosque samples are about the same as those computed for spheres settling through water, but larger hydraulic equivalent sizes (in the coarser and very fine sizes) are considerably larger than those computed from the formula.

Analysis of the curves show that either the large equivalent sizes in the finest sizes should be smaller or the smaller equivalent sizes in the immediately coarser sizes should be larger. As the curves are presented in Figure 10, heavies in the finest sizes are equivalent hydraulically to the same light minerals as the heavies in the slightly coarser sizes. This seems impossible.

To check the position of the best value points, data from a duplicate analysis of sample F were obtained. Substitution of the duplicate F for the original F causes no essential change in the shape or position of the best value curves of Figure 10. Exclusion of data from samples B and C generally does not change the position of the points in the coarser sizes but does lower the lower points for some minerals. This would seem to indicate that at least part of the curvilinear shape of the curves is caused by experimental or sampling errors. The Bosque samples thus do not give definite evidence concerning change of hydraulic equivalent size with size, other than to indicate that such change, if present, is probably of small magnitude in the size grades that are important at Bosque.

HYDRAULIC EQUIVALENT SIZE AND GRAIN SHAPE

In using hydraulic ratios to compare heavy-mineral compositions, weights of heavy minerals rather than their frequency by number are used. Because most of the minerals cannot be conveniently segregated from one another and weighed separately, the weights must be determined by an indirect method. The frequency by number is first obtained and then corrected for specific gravity to given weight percentages. These weight percentages are then multiplied by the weight of the nonmagnetic heavy-mineral fraction. In the specific-gravity correction, however, it is assumed that the average volume of the different heavies is essentially the same. However, if number frequencies were determined for the entire range of sizes in an unsieved sample, such minerals as zircon and ilmenite that, because of high specific gravity and/or relative availability, are concentrated in the finer sizes would have disproportionately high number frequencies, and the volume assumption would be greatly in error.

To reduce such errors, sieves are used to size the heavy and light minerals. However, sieves separate grains on the basis of shape as well as size, and consequently the reduction of one error introduces another factor that must be evaluated—namely, the relation between shape and the size of grain passed by sieves. It is pertinent to inquire how this relation affects the equivalent hydraulic size.

The relation of shape to size of grain passing sieves has been discussed previously by the writer (Rittenhouse, 1943a). It was found that in a sieve separate the average intermediate diameter increases as flatness increases. Thus, in the same sieve separate, the flat grains of large intermediate diameter will be associated with more spherical grains of smaller intermediate diameter. The flatter or more elongated grains would be expected to settle through water at a slower rate than spherical grains and then be of smaller hydraulic equivalent size. Actually, however, the flatter grains appear to have larger volumes and consequently greater weights than would spheres retained or passed by the same sieves. Thus some compensation in settling rates would be expected.

That such compensation exists and that, for a fairly wide range of shapes, it is extremely good, was shown by a comparison of the intermediate grain diameters as determined by microprojection and the settling rates of grains from the same size grades (Rittenhouse, 1943b). Although the intermediate diameters of 30 to 50 per cent of grains are larger than the rated openings of the sieve through which the grains have passed, the irregularly shaped grains settle at just about the same rate as spheres that would be passed or retained by the same sieves. These measurements were made on grains that had an average flatness ratio (short diameter/intermediate diameter) of about 0.74.

Because most of the heavy minerals have flatness ratios of about the same order of magnitude, it seems probable that most of the heavy minerals would settle at about the same rates as spheres of the same material. If this is true, then differences in shape caused by sieving would have no effect on the hydraulic equivalent sizes. The flatness ratio of mica, and perhaps blue-green hornblende, are sufficiently different, however, so that their settling velocities and their hydraulic equivalent sizes might be less than expected from their specific gravities. Data are not available for mica, since only part is in the heavy-mineral separate. For blue-green hornblende, which appears to have a hydraulic equivalent size slightly less than 0.2ϕ in comparison with brown and green hornblende, which are slightly more than 0.2ϕ (Table 7), shape may be important.

Actually, the compensation effect introduced by sieving simplifies interpretation of the relation between shape and hydraulic equivalent size, at least insofar as the settling rates are concerned. From shape calibration curves (Rittenhouse, 1943a), it is possible to estimate what the hydraulic equivalent sizes might be if they were based on the measurement of intermediate diameters rather than on sieve units. For minerals that are flatter than the light minerals, the hydraulic equivalent size would be greater by about $.07\phi$ units for each .10 difference in flatness. For minerals that are less flat than the lights, the hydraulic equivalent size would be less by about $.07\phi$ units for each .10 difference in flatness.

Although some experimental data are available on the relation between grain shape and transportation of pebbles as bedload (Einstein, 1937; Ho, 1939), the writer knows of no similar data on bedload movement of sand. Theoretical considerations would indicate that shape is not important in bedload transportation of fine sand. At low-water stages, the bed sediments characteristically move downstream in ripples, the sediment in each ripple apparently moving as a unit, regardless of difference in

size or grain shape. In such transportation, grain shape would be an important factor only during the initial "picking up" of the sediment that forms the ripple. With increasing water velocity, the size of the ripples would increase, but the unity of each ripple should not be affected. With further increase of velocity, suspended-load movement would become predominant, and the settling velocity would be the important factor. Difference in grain shape resulting from sieving would thus not appear to affect the hydraulic equivalent sizes.

RELATIVE AVAILABILITY

The hydraulic ratio measures directly the relative availability of heavy and light minerals of equivalent hydraulic value in the stream load. Consequently, comparison of the hydraulic ratios for different sizes also shows how relative availability changes with size. The average hydraulic ratios for 16 minerals in 4 size grades in the Bosque samples have been presented in Table 11.

For all minerals except hypersthene, the relative availability is lower in the coarsest size grade than it is in some finer size grade. Examination of other data (Rittenhouse, 1943b; 1943c) indicates that this is usual for most minerals in the Rio Grande and its major tributaries. The most probable cause appears to be a deficiency of large-sized heavy minerals in the source rocks.

In general, the minerals at Bosque appear to be divisible into three groups with respect to the relation between availability and size. In one group, which includes zircon, barite, tourmaline, apatite, brown hornblende, and green hornblende, relative availability increases with decreasing size over the entire range presented in Table 11. In a second group, which includes magnetite, ilmenite, diopside, titanite, kyanite, garnet, and blue-green hornblende, the relative availability increases with decreasing size to the .175–.124 mm. or .124–.088 mm. size grade and then decreases. In the third group, which includes pyroxene and hypersthene, the relative availability is essentially the same in all four size grades.

Data on the relative availability are furnished also by the $<.061$ size grade, but for most minerals its interpretation is not clear. The $<.061$ mm. size grade includes a wide range of small sizes, and the hydraulic ratios are average values for this entire range. For zircon, hypersthene, pyroxene, titanite, garnet, and apatite, the hydraulic ratios are notably larger than those in size grades $>.061$ mm. This can only mean that for some sizes in this grade these minerals are available in larger amounts than in the coarser size grades. Whether the availability increases progressively with decreasing size to the finest sizes present or whether there is an increase in availability and then a decrease cannot be determined. For the other minerals, the hydraulic ratios in the $<.061$ mm. size grade are about the same as in the .088–.061 mm. size grade. This also could be interpreted in several ways—*i.e.*, to mean fairly constant relative availability in all sizes $<.061$ mm., an increased availability and then a decreased availability, or a decreased availability and then an increased availability.

In spite of the difficulty of interpreting the data for the $<.061$ mm. size grade, the other four size grades yield information that partially explain some of the apparent discrepancies in position and slope of the heavy-mineral size-distribution curves. The relatively low availability of zircon in the coarse size grades in comparison with

magnetite and ilmenite, which are both of higher specific gravity, appears to account for the much finer average size of the zircon. The low relative availability of blue-green hornblende in both the coarse and fine sizes appears to explain why it is better sorted than pyroxene, whose relative availability is essentially the same in the four size grades for which the best data are available (Fig. 2).

SIZE DISTRIBUTION AT DIFFERENT PLACES IN THE STREAM

At different places in the same stream such factors as slope, width, depth, and roughness of the channel will not be the same. Consequently, hydraulic conditions will vary, not only with time and stage, but with place. Commonly, progressive downstream change in the hydraulic conditions will be reflected by progressive downstream decrease in the average grain size of the channel deposits. These differing hydraulic conditions will be accompanied by differing size distribution of the heavy minerals, similar to the differences that occur at any one transverse section of the stream. No change in the hydraulic ratio results.

At different places in the same stream, the relative availability and the physical characteristics of the minerals may be different, and this may result in changed equivalent hydraulic size and/or hydraulic ratios. Such changes may be progressive, as when various factors constantly act on the sediment during its downstream transportation, or may be sudden, as when new debris is introduced by tributaries. The changes in relative availability and/or physical characteristics may be caused by (1) selective wear or breakage, (2) selective sorting that does not follow the hydraulic equivalent size concept, (3) selective weathering or authigenic growth, (4) progressive change in source material, (5) floodplain contamination, and (6) tributary contamination. The change produced by each of these and the probable importance of such changes will be discussed briefly.

(1) Selective wear or breakage. All grains, as they are transported downstream, will be reduced in size, but the rate at which such reduction occurs will be selective. Presumably soft minerals will be reduced in size and will become rounded more rapidly than will hard minerals of the same original shape. Minerals with good cleavage will tend to split and thus change their sphericity or roundness or both at a different rate from minerals that lack good cleavage. Size of grain also is probably a factor in the absolute rate of wear of different minerals. The net effect of all these factors will be a differential change in the relative availability and the physical characteristics (mainly shape and roundness) of the sediment in different parts of the stream. These changes may be accompanied by changes in the hydraulic equivalent size and in the value of the hydraulic ratio.

Assuming no change in hydraulic equivalent size, the change in hydraulic ratio of any size grade will depend on the net loss or gain resulting from addition of grains from coarser size grades, loss of grains to finer sand grades, and loss of very fine particles (silt and clay). Thus when a heavy is reduced in size more rapidly than the light minerals of equal hydraulic value, the hydraulic ratios in the coarser size grade will be smaller, those in the intermediate size grades will show moderate gains or losses, and those in the finest grades will increase. When the differential loss of very fine particles is great, the hydraulic ratios may decrease in all size grades. When the

light minerals are reduced in size more rapidly than the heavy, the hydraulic ratios for the coarse size grades will increase, those for the intermediate size grades will not change greatly, and those for the fine size grades will decrease. Great differential loss of very fine particles may increase the hydraulic ratios in all size grades. Decrease in the hydraulic equivalent size of minerals that wear more rapidly than the light minerals will reduce, increase, or have little effect on the hydraulic ratios depending on the size distribution of the deposit and the size distribution in the stream load.

Most available evidence indicates that wear is a relatively slow process. In their Mississippi River studies Russell and Taylor (1937) found that selective destruction of "less resistant" minerals appears to be of slight consequence between Cairo, Illinois, and New Orleans, Louisiana, a distance of 950 miles. In the Rio Grande, many grains show little evidence of either wear or breakage. At Bosque, New Mexico, the original crystal form of the easily abraded minerals apatite and hypersthene commonly has been only slightly modified. At the same locality, many grains of hornblende and pyroxene are characteristically sharp cornered, and some grains of these minerals have needlelike projections. Preservation of such features after a minimum of 60 miles transportation (from above Alameda, New Mexico) must indicate very slow wear.

Theil's (1940) tumbling barrel experiments with quartz, feldspar, garnet, tourmaline, hornblende, and apatite show that differential wear occurs but is very slow. Apatite was reduced in size most rapidly, quartz least rapidly. Even after travel of 5000 miles, however, about 15 per cent of the apatite of the coarsest size (2–1 mm.) still remained in that size grade. Thiel's experiments apparently simulated bedload transportation. In streams like the Rio Grande, where suspended-load transportation of fine sand is important, the absolute and differential rates of wear may be expected to be much slower. In mountain streams of high gradient, or streams in which crushing of sand by gravel is possible, differential wear may be more rapid. In such streams cleavage and brittleness may be more important factors than hardness.

(2) Selective sorting that does not follow the hydraulic equivalent size concept. One question that will probably be raised by some readers concerns the occurrence of heavy-mineral concentrates in stream sands and their relation to the concept of hydraulic equivalence. Genetically, concentrates of heavy minerals may form in two ways. Some concentrates result from selective erosion, others from segregation during transportation. If sands containing magnetite or other dark-colored heavy minerals are placed in a stream (as by undercutting of a bank), a dark heavy-mineral concentrate will form at the points of current impingement, the light-colored minerals having been selectively removed. If the current velocities are low, ripples composed only of light-colored minerals will form a few feet downstream. Diversion of the current at this time leaves an "erosion" concentrate.

If erosion continues, however, both dark and light minerals will be removed. The ripples downstream will be composed of both dark and light minerals, the dark minerals being concentrated at or near the crest—apparently forming a ripple on a ripple. Each ripple then appears to move downstream as a unit, neither gaining nor losing

dark or light material. Apparently no selective action is involved in such downstream transportation.

When the ripple goes over the edge of a hole or a small delta in the channel, dark and light minerals form separate layers in the foreset beds. Such "deposition" concentrates may also form on bars, where the reduced water depth and velocity apparently results in a rather uniform distribution of both dark and light minerals in thin horizontal beds. Provided enough layers are sampled, the concentration of dark and light heavies from such deposits will be the same as that in the ripples.

In bedload transportation, downstream change in the hydraulic ratios resulting from selective sorting that does not follow the hydraulic equivalent size concept appear to result from erosion or "picking up" factors. Although less is known about concentration that occurs during higher stages when the finer size grades are carried in suspension, picking up rather than deposition would appear to be of most importance. Because such selective action permits the heavies to lag behind the light minerals whose hydraulic size otherwise is the same, the deposits would contain too many heavies and too few lights. The hydraulic ratios as determined from the bed deposits would thus be too high. Presumably, high density heavies would be effected more than those of low density. This may account for part of the difference between the hydraulic ratios in transit and bed deposits at Escondido, New Mexico.

If such selective action occurred in all streams to the same relative extent—*i.e.*, the hydraulic ratios in each stream being 10 or 20 or 30 per cent too high, it would have no effect whatsoever on the comparison of the deposits. Only when the selective action is not the same will the comparisons be in error.

In the selective action described above, differences in specific gravity would appear to be of first importance. Studies by Russell and Taylor (1937) and Pettijohn and Lundahl (1943) indicate that grain shape also may be significant. They found that the average sphericity of the light minerals decreased with distance from the source. Presumably, such a shape change would also occur for heavy minerals. If so, the hydraulic equivalent size and the hydraulic ratio may increase, stay the same, or decrease, depending upon the relative rate of sphericity change for the light and heavy minerals.

(3) Selective weathering or authigenic growth. Quartz is much more stable chemically than many of the heavy minerals in stream sands. Apatite, for example, is much more soluble than quartz, and the amphiboles (hornblende), pyroxenes, and ilmenite are more easily altered. Thus, differential weathering is a factor in changing the relative availability and physical characteristics of minerals during their downstream transportation. The quantitative importance of this factor over distances of a few hundred miles had not been evaluated. Thiel's (1940) tumbling barrel experiments showed that measurable quantities of apatite, hornblende, and feldspar were dissolved in 5000 miles of transportation, but the experiments did not indicate how much of this solution was from the original grains and how much from the many tiny chips removed by attrition.

Field evidence on the relation of weathering to distance of transportation is meager. In the Rio Grande some grains of apatite and garnet show solution cavities, and all gradations between ilmenite and its alteration product leuxocene occur. However,

the proportion of such grains does not appear to change with increasing distance from the source. Changes in size or physical characteristics (mainly shape) by weathering probably is a very slow process in the Rio Grande. Russell reached essentially the same conclusion in his Mississippi River investigation. Downstream change in hydraulic ratios from weathering will probably be very small.

Concerning authigenic or secondary growth of minerals during downstream transportation, very little is known. Grains of pyroxenes showing authigenic terminations are fairly common in Rio Grande sands, but there appears to be no change in the number of terminated grains or in the size of the terminations with distance of transport. It seems most probable that the terminations were developed before the grains left the source area and that they have not been destroyed during downstream transportation.

(4) Progressive change in source material. If the rates of erosion increase in part or all of a drainage basin, subsoils are exposed by sheet erosion, and C-horizons by gullying. To the extent that the mineralogical composition of the several soil zones differ, the mineral composition of the sediment delivered to the streams would change progressively. The extent of the resulting downstream change in mineral composition would depend on the relative importance of two factors—namely, the rate of change in composition in the source area, and the average rate of downstream transportation. If different sizes of debris are not transported at the same average rate, the downstream change in composition may not be the same for different sizes of the same sediment.

Differential change in the rate of contribution from various parts of the drainage area will also tend to produce progressive downstream changes in mineral composition. Such differential rates of contribution are probably the rule rather than the exception. Here again, the change will depend on the rate of change in the source area and the average rate of downstream transportation. In the Rio Grande channel between San Acacia and San Marcial, New Mexico, the heavy-mineral composition has been changed greatly since about 1870 by increased contribution of sand from the Rio Salado (Rittenhouse, 1943c).

(5) Flood-plain contamination. In many streams, the lateral migration or widening of the channel by bank erosion is an important process. In lateral migration, erosion on the outside of bends is wholly or partially compensated by deposition on the inside of bends. Although no increase in sediment load necessarily results, the mineral composition may be greatly modified. Channel widening, in contrast, will increase the sediment load as well as modify the mineral composition. Similar increase in sediment load and mineral composition may be caused by trenching or by local erosion of the bedrock. The extent to which the hydraulic ratios will be modified by such floodplain contamination depends on the amount of sediment added and its mineral composition. If the shape of the minerals in the new sediment differs from that in the old, some change in hydraulic equivalent size may also occur.

(6) Tributary contamination. Sediment introduced by tributaries immediately modifies the hydraulic ratios in the main stream. The extent of change will depend on the difference in mineral composition of the tributary and main stream sands and on the relative amounts of sand from each. Hydraulic ratios of some minerals may

be increased; ratios of others may be decreased; and ratios of the remaining minerals may not change. In the Rio Grande, all these changes have been noted (Rittenhouse, 1943b; 1943c). Notable differences in physical characteristics of the sediment may affect the average hydraulic equivalent size, as may notable differences in the mode of transportation (bedload or suspended load) of the tributary sediment.

METHODS IN COMMON USE

GENERAL CONSIDERATIONS

In the preceding sections of this paper, the data on the occurrence of heavy minerals in six samples from the Rio Grande at Bosque have been presented, several factors governing the occurrence of heavies in river deposits have been outlined, and the hydraulic ratio has been presented as a new and more generally useful basis of comparing heavies in river deposits. Other investigators have used or recommended other methods of comparing heavy minerals. In general, these other methods are simpler and involve less expenditure of time per sample worked than do hydraulic ratios. Consequently, they should be used whenever they are applicable. The Bosque data and the principles of heavy-mineral occurrence that have been outlined provide a means of determining how useful these other methods may be and the extent to which they may be applicable to various types of investigations. Insofar as possible[8] the conclusions reached will be verified by statistical tests of significance.

Some investigators use the presence or absence of one or more "diagnostic" minerals. Other investigators determine, by estimation or counting, the relative frequency by number of the minerals in the heavy-mineral fraction. The mineralogy may be determined for the whole sample, for a single size grade, or for combinations of several size grades. One common practice is to compare these number frequencies, either directly, if the same number of grains have been counted in all samples, or as mutual percentages. In another method (Pettijohn, 1931) one mineral (garnet) is made a base to which the relative proportion of other minerals is compared. Cogan (1935) proposed a somewhat similar scheme but used the ratio of each component to that in a "reference" sample.

Weight percentages of the entire heavy-mineral fraction and of magnetite have also been used to a limited extent. Presumably, weights of mineral species other than magnetite would also have been used, had a practical method of segregating and weighing the different species been available.

Most heavy-mineral investigations have one or more of the following objectives: (1) to describe the mineral composition of a particular deposit; (2) to establish the similarity or dissimilarity of samples, generally for the purpose of geologic correlation; (3) to determine the change in mineral composition within a series of related samples so that factors related to the occurrence of heavies may be discovered and evaluated; (4) to locate the sources or to evaluate the relative importance of various sources of a deposit; (5) to provide data from which the past history of a deposit

[8] Because the Bosque samples were sieved and the minerals in each size grade examined separately, the data are not well adapted to testing those methods based on examination of unsieved samples. By using reasonable assumptions, however, it has been possible to compute the mineral composition in the whole sample from that in the various parts and to test the methods with these data. Because of the assumptions and because application of tests of significance to such results is difficult, the verification of conclusions regarding unsieved samples is less complete than desired.

may be interpreted; and (6) to find and aid the exploitation of economically useful minerals. The usefulness of any method for attaining these objectives depends to a considerable extent on the accuracy needed. For some problems, methods giving qualitative data may be satisfactory; for others qualitative data may be inadequate or misleading. Consequently, guiding principles rather than hard and fast rules will be stressed in the discussion to follow.

TABLE 12.—*Mutual percentages by number of eight selected minerals in actual and postulated samples at Bosque*

Sample	Size Grade	Ilmenite	Pyroxene	Hypersthene	Blue-green hornblende	Green hornblende	Zircon	Apatite	Garnet
	Mm.								
A	.250–.175	8.6	31.6	11.5	34.6	11.5	.....	1.6	.7
G	do	35.0	17.4	8.2	18.1	11.3	.6	2.1	7.2
X	do	26.7	23.5	8.9	23.2	11.3	.....	1.9	4.2
A	.088–.061	70.2	5.3	2.1	4.3	3.9	9.2	2.4	2.6
A	All	66.3	5.5	2.7	5.5	3.8	9.8	3.4	3.0
G	do	62.4	7.4	3.7	7.0	5.4	8.2	3.2	2.8

DIAGNOSTIC MINERALS

In using diagnostic minerals, the entire sample or one or more size grades may be examined, and the presence or absence of selected mineral species noted. The presence or absence of certain species may, in some cases, be sufficient to complete objective 2 and partially solve objectives 1, 4, 5, and 6.

If a mineral occurs only in small grains, however, it must be used with caution as a diagnostic mineral, particularly if a size grade rather than the entire sample is examined. At Bosque, zircon is such a mineral, being absent from the coarser size grades in all samples except G (Table 3). If entire samples are examined, such minerals as zircon would be absent only when the samples contained no sediment of fine size. Similarly, such minerals may be used if a size grade common to all samples is studied.

But the presence or absence of zircon, or minerals like it, is of questionable diagnostic value if single size grades having the same relative position with respect to the size distribution of the samples are used. This is well shown in Table 12 in which sample X[9] has no zircon, and sample A has over 9 per cent zircon. In each sample, the size grade selected for comparison is half way between the modal grade and the finest material in the size distribution.

SCALES OF ABUNDANCE

From estimates or actual counts, some workers classify grains in order of abundance, using such terms as abundant (A), common (C), scarce (S), and rare (R), or

[9] The textural range of the Bosque samples was not great enough to illustrate this point. Since the weight or number frequencies of any sample of known or postulated size distribution may be computed from the hydraulic ratios (Table 11) and the hydraulic equivalent sizes (Table 7), the mineral composition of a sample having the same sorting as sample G but an average grain size one Wentworth size grade larger was calculated. Percentages for all samples in Table 12 are mutual percentages for the minerals shown.

an arbitrary scale of numbers. The entire sample or selected size grades may be examined. To illustrate the discussion of this method by use of the Bosque data, the following classification will be adopted:—VA, >60 per cent; A, 30–60 per cent; FA, 15–30 per cent; VC, 7.5–15 per cent; C, 3–7.5 per cent; FC, 2–3 per cent; S, 1–2 per cent; R, 0–1 per cent; 0, absent. Of the Bosque samples, A and G differ most in

TABLE 13.—*Abundance* of eight selected minerals in actual and postulated samples at Bosque*

Sample	Size Grade	Ilmenite	Pyroxene	Hypersthene	Blue-green hornblende	Green hornblende	Zircon	Apatite	Garnet
	Mm.								
A	.250–.175	VC	A	VC	A	VC	O	S	R
G	do	A	FA	VC	FA	VC	R	FC	C
X	do	FA	FA	VC	FA	VC	O	S	C
A	.088–.061	VA	C	FC	C	C	VC	FC	FC
A	All	VA	C	FC	C	C	VC	C	FC
G	do	VA	C	C	C	C	VC	C	FC

* Abundance symbols represent percentages as follows:—VA, >60; A, 60–30; FA, 30–15; VC, 15–7.5; C, 7.5–3; FC, 3–2; S, 2–1; R, 1–0; and O, Absent.

texture and should show the greatest difference in relative abundance. The abundance data are presented in Table 13.

For the entire samples, the abundance differs only slightly in samples A and G, and the similarity of the two samples is apparent. For a size grade common to all samples, or for a size grade having the same relative position with respect to the size distribution of the samples, however, the differences are so great that a decision on their similarity or dissimilarity becomes a matter of personal opinion. In samples having a greater range in average size and degree of sorting, the differences in abundance should be greater than those in Table 13, both for entire samples and for selected size grades.

For some qualitative work required by objectives 1, 2, 4, 5, and 6, the use of abundance scales, particularly those based on examination of entire samples, appears to be justified. When samples differ by a $\sqrt{2}$ size grade or more in average grain size, however, differences in abundance, particularly for single size grades, may be misleading.

The abundance method is based entirely on number percentages in the heavy-mineral separate or some selected part of it. The percentage of heavy minerals by weight is not considered. Consequently, deposits that are similar if compared on the basis of numbers actually may not be from the same source or have the same history. Misleading conclusions concerning the relative importance of various sources may also be obtained if the weight of heavies is not considered.

PERCENTAGES BY NUMBER

General statement.—In many investigations, the percentages by number of various minerals in the heavy-mineral separate are determined by counting, and the percentages in different samples are compared to determine the degree of similarity or

difference. If the percentages are identical, there is no question regarding the statistical similarity of the samples, though it is recognized (Dryden, 1935) that geological formations of different age or history might have identical or very similar mineral frequencies. If the percentages differ, as they usually do, the attempt to describe and interpret the meaning of various degrees of difference, particularly when a large number of samples are involved, is awkward, difficult, and a matter of personal judgment, unless some objective measure of similarity or difference is available (Krumbein and Pettijohn, 1938). This has led to the application of statistical measures to the comparison of mineral compositions, measures that are based on the theory of probability.

When statistical methods are used, however, it is assumed that the deposits to be compared are each homogeneous with respect to mineral composition—*i.e.*, that differences in mineral composition in a set of duplicate samples from the same deposit would be caused only by chance errors of random sampling. Such factors as variation in hydraulic conditions at different times and places of deposit may influence the mineral composition within a single deposit sufficiently to invalidate this assumption. Unfortunately, the magnitude of such nonsampling variations cannot be approximated on the basis of probability. Consequently, if an objective measure of similarity or difference is to be used, nonsampling variations must be evaluated experimentally or eliminated through choice of a suitable method of comparison.

Same size grade.—In the same size grades of different samples at Bosque, the number percentages of heavy minerals varies. For some minerals such differences are large, as for ilmenite for which, in the .175–.124 mm. size grade of the six samples, the range is from 6.0 to 35.8 per cent (Table 3). For other minerals the differences are small, as for brown hornblende which, in the same size grade, has a range of from 4.6 to 6.0 per cent. To determine whether these differences might be due to errors of random sampling, the frequency of occurrence of 11 minerals[10] in the 6 samples was compared by the chi-square method (Eisenhart, 1935; Snedecor, 1940). Chi-squares for the .250–.175 mm., the .175–.124 mm., the .124–.088 mm., the .088–.061 mm., and the <.061 mm. size grades were, respectively, 125, 207, 219, 184, and 186 (df = 50). Random sampling should give a chi-square value greater than about 75 only 1 time in 100. The differences between samples are highly significant for all size grades compared.

There was still the possibility that the highly significant differences in mineral composition might be due largely to the influence of one or two of the six samples. To eliminate this possibility, all possible combinations of four samples in the .175–.124 mm., the .124–.088 mm., and the .088–.061 mm. size grades were compared by the chi-square method. For none of these combinations was chi-square less than that to be expected 1 time in 100 as a result of random sampling.

These highly significant differences in heavy-mineral composition are not caused by nonrandom errors in the laboratory analysis of the samples. For sample F and a duplicate split from the same composite, the differences in mineral composition, when expressed as number frequencies, did not exceed those to be expected from ran-

[10] Ilmenite, pyroxene, hypersthene, blue-green, green, and brown hornblende, tourmaline, zircon, apatite, garnet, and diopside (C).

dom sampling for the .250–.175 mm., the .175–.124 mm., the .124–.088 mm., the .088–.061 mm., or the <.061 mm. size grades. In another test, the mineral composition in eight splits from the .124–.088 mm. size grade of a Rio Grande sample from Albuquerque, New Mexico, did not differ significantly (Rittenhouse and Bertholf, 1942). For beach sands, the nonsignificance of laboratory errors has been demonstrated by Krumbein and Rasmussen (1941).

Since the highly significant chi-squares are not caused by nonrandom errors in laboratory analysis, they must reflect highly significant differences in heavy-mineral composition (when expressed as number percentages) in the sand deposits at a transverse cross section of a river. If varying hydraulic conditions and other factors so modify the mineral composition of the closely spaced and texturally similar Bosque samples, it is difficult to see how statistical measures based on a size grade common to all samples can be used widely to compare the mineral composition of sediments. In most investigations, the textural range will be greater than that at Bosque, and consequently the mineral composition will differ even more.

It should be emphasized that the differences in mineral composition resulting from varying hydraulic conditions cannot be eliminated by counting more grains per sample, because the samples as brought to the laboratory are dissimilar. Nor, insofar as the comparison of samples from different localities is concerned, can the differences be reduced or eliminated by combining two or more spot samples into a composite, as recommended by Krumbein and Rasmussen (1941). It is true that such composites more nearly approximate the average mineral composition for the average hydraulic conditions existing at each sampling locality. But inherent differences in composition due to deposition under the different magnitudes or ranges of hydraulic conditions at various localities will persist. To determine experimentally the variation due to hydraulic conditions, the *entire* range and magnitude of hydraulic conditions under which *all* samples to be compared were deposited must be considered. Rarely will the necessary range be present. Probably comparison of number percentages of heavies from a single size grade will not be more useful than scales of abundance in reaching any of the six objectives.

Averaging size grades.—Russell (1936), recognizing that the heavy-mineral composition of sands varied with average size and sorting, averaged the composition of two size grades. He found that the average of a size grade common to all samples and a size grade "midway between the grade containing the maximum amount of material and the finest material" gave the best basis of comparison. Similar comparisons were made for samples A, D, F, and G of the Bosque suite, using the .088–.061 mm. size grade as that common to all, and the .175–.124 mm. (samples D and G), or the .124–.088 mm. grade (samples A and F) for the other size grade. A chi-square test indicates that the differences in mineral composition of these averages are highly significant.[11] This would indicate that averaging two size grades does not eliminate inherent differences in mineral composition at different parts of a trans-

[11] Combining size grades complicates statistical analysis, since the number of grains counted is an important factor in the tests. If the total number of grains counted in both size grades is used, the chi-square will be twice as large as if the arithmetic mean is used. In the test above, the differences were highly significant when the arithmetic mean was used. The differences would also have been highly significant if the total number of grains in both size grades had been used.

verse river section. Consequently, if statistical measures cannot be applied, the method is little better than that in which a single size grade is used.

Entire sample.—The number percentages of heavy minerals in all size grades of the six Bosque samples were calculated[12] and are presented in Table 14. A comparison of the percentages in this table with those in Table 3 indicates a lesser variation in

TABLE 14.—*Percentage by number of heavy minerals at Bosque*
As computed for entire samples

Sample	Ilmenite	Pyroxene	Hypersthene	Blue-green hornblende	Green hornblende	Brown hornblende	Tourmaline	Zircon	Apatite	Garnet	Diopside (C)	Others
A	46.9	3.9	1.9	3.9	2.7	.8	1.6	6.9	2.4	2.1	.9	26.0
B	34.7	4.9	1.0	6.7	4.4	2.1	2.0	7.6	1.8	1.3	.7	32.8
C	31.0	5.3	1.4	5.8	4.7	1.6	2.5	7.6	3.2	1.6	1.5	34.0
D	37.6	4.8	1.5	4.6	3.6	1.6	1.5	8.9	3.6	1.5	1.2	29.8
F	32.4	3.1	1.8	4.4	3.8	1.6	1.5	6.9	2.6	2.2	.9	38.8
G	44.6	5.3	2.6	5.0	3.9	1.6	1.9	5.9	2.3	2.0	.8	24.0

number percentages for the entire samples than for selected size grades. For ilmenite in the entire sample, the range is from 32.4 to 46.9 per cent, a difference of 14.5 per cent, whereas for the .175–.124 mm., the .124–.088 mm., the .088–.061 mm., and the <.061 mm. size grades the differences are about 30, 28, 25, and 28 per cent respectively.

Applying chi-square tests to this calculated data requires some assumption about the number of grains counted in each sample. Obviously, it is not correct to total the number of grains counted in the various size grades, because the three finest size grades are much more important than the others in determining the number percentages. However, the number must be greater than that in the finest size grade (which is most important in determining the number percentages). If this minimum number is used as a limiting approximation, a chi-square test indicates that the chances are about 1 in 20 that the differences in mineral composition in the samples at Bosque could be due to chance errors of sampling. For twice this minimum number of grains—a more reasonable assumption—the chances would be much less than 1 in 100 that the differences are due to sampling. Thus, it seems unlikely that statistical methods of comparison can be applied to number percentages of entire samples, and very unlikely that they may be applied where the difference in texture between samples exceeds the $\sqrt{2}$ size grade range existing at Bosque.

Where a series of samples changes progressively in texture, as along a beach or a

[12] It was assumed that the number of grains per unit weight of heavies was inversely proportional to the cube of the grain diameter (1.00, 2.83, 8.00, etc., for $\sqrt{2}$ size grades). For each sample the weights of nonmagnetic heavies were multiplied by these factors and the product for each size grade divided by the sum of the products for all size grades to give a weighting factor for each size grade in the sample. The number percentages in each size grade were then multiplied by the weighting factor for that grade. For each mineral the sum of these products for all grades was divided by the sum for all minerals to give the number percentage for the entire sample. Incidently, the three finest grades have a weight of 88 per cent or more in determining the final percentages. Therefore, if a sample is divided into a coarse and a fine part, and the heavies from only the finer part examined, the number frequencies so obtained will be essentially the same as those in the entire sample. Use of such partially sized materials will facilitate laboratory and petrographic work.

river, progressive changes in number frequencies may reflect only the textural differences at the various sites of deposit and not progressive sorting, wear, or other changes in mineral composition. This will be true regardless of whether the entire samples or selected size grades in them have been examined. In Figure 9B, the progressive changes in the number percentages of magnetite and pyroxene that might accompany progressive change in average grain size have been plotted. To attain objective 3, the effect of hydraulic conditions must be eliminated before the importance of other fundamental characteristics may be determined.

Coefficient of determination.—In the preceding discussion of number frequencies, no mention was made of a statistical measure designated the "coefficient of determination" (r^2) by Dryden (1935). This coefficient ranges from 1 to 0. When r^2 is 1, the percentages in the two samples are identical (or inversely proportional); when r^2 is 0, no species are common to both samples. The Bosque data have yielded some information on the use and the limits of applicability of this measure.

Using the number percentages for the entire samples, very high r^2 values were found. For the same size grades, r^2 was very high (.99) for some pairs of samples but was as low as .10 for other pairs (A and G, .175–.124 mm. size grade). If r^2 may range from .99 to .10 in the same transverse cross section of a river, it is difficult to see how this measure can be of value in comparing mineral compositions from different formations or parts of the same formation, especially where the textural range is great. If the entire samples rather than selected size grades are examined, however, the measure may be useful, at least for a textural range comparable to that at Bosque.

It should be noted, however, that values of r^2 cannot be correlated with significance or nonsignificance as determined by the chi-square method. For the .124–.088 mm. size grade of samples A and G, r^2 is .99 though the chi-square indicates highly significant differences between the samples. In contrast, for the .250–.175 mm. size grade of samples D and G, r^2 is .87, though the chi-square method indicates that the samples do not differ significantly.

It also appears that when there is a flood of one mineral in the two samples being compared, r^2 will be high regardless of the relative proportions of the other minerals in the samples. For example, in a pair of samples containing five minerals that have number percentages of 75 and 50, 10 and 30, 0 and 5, 15 and 0, and 0 and 15, r^2 is .64. If in a second pair of samples, the number percentages were 25 and 20, 12 and 20, 15 and 15, 21 and 20, and 27 and 25, r^2 would be .44. Probably most geologists, however, would consider the second pair of samples more alike than the first pair. With this the writer would agree. Incidently, if the number percentages had been 40 and 0, 30 and 10, 20 and 20, 10 and 30, and 0 and 40 for the five minerals, r^2 would have been 1.00. While it is not the writer's purpose to discuss the statistical basis of Dryden's coefficient of determination, further critical study seems necessary before r^2 is accepted as a basis for comparing mineral compositions.

RATIOS BY NUMBER

Same size grade.—Because of several advantages, some workers have used ratios by number in preference to percentages by number. Unless the similarity or differences between ratios can be determined by an objective measure, however, correlations and other conclusions based on ratios must be a matter of personal opinion.

To determine whether statistical measures based on laws of probability can be applied, ratios between selected minerals at Bosque were computed, and the differences between them were compared with the differences to be expected from random sampling. Because of time limitations, such comparisons were made only for samples A and G.

TABLE 15.—*Ratios and their errors for selected heavy minerals in samples A and G at Bosque*

Minerals	Size Grade					
	.175–.124 mm.		.124–.088 mm.		.088–.061 mm.	
	A	G	A	G	A	G
Same specific gravity						
Zircon/Ilmenite	0.072 ± .040	0.025 ± .024	0.059 ± .013	0.045 ± .009	0.131 ± .013	0.116 ± .016
Blue-green hbl./Pyroxene	1.96 ± .25	1.04 ± .14	1.29 ± .15	1.32 ± .19	.82 ± .12	1.09 ± .19
Green hbl./Pyroxene	.68 ± .11	.53 ± .09	.95 ± .12	.98 ± .14	.73 ± .12	.94 ± .14
Brown hbl./Pyroxene	.26 ± .07	.26 ± .06	.25 ± .06	.21 ± .06	.29 ± .07	.43 ± .09
Green hbl./Bl. gr. hbl.	.35 ± .05	.82 ± .10	.74 ± .09	.74 ± .10	.90 ± .15	.86 ± .13
Brown hbl./Bl. gr. hbl.	.14 ± .03	.25 ± .06	.19 ± .04	.16 ± .04	.35 ± .09	.39 ± .07
Brown hbl./Green hbl.	.39 ± .09	.48 ± .12	.26 ± .06	.21 ± .06	.39 ± .09	.45 ± .09
Different specific gravity						
Pyroxene/Ilmenite	1.26 ± .19	.18 ± .02	.211 ± .024	.103 ± .014	.075 ± .010	.114 ± .016
Bl. gr. hbl./Ilmenite	2.48 ± .35	.19 ± .02	.273 ± .027	.136 ± .016	.058 ± .009	.123 ± .016
Green hbl./Ilmenite	.86 ± .14	.10 ± .02	.202 ± .024	.101 ± .013	.055 ± .009	.106 ± .015
Brown hbl./Ilmenite	.33 ± .08	.05 ± .01	.052 ± .013	.021 ± .006	.022 ± .006	.048 ± .011
Garnet/Ilmenite	.12 ± .05	.10 ± .02	.084 ± .013	.031 ± .008	.039 ± .008	.058 ± .012
Zircon/Pyroxene	.057 ± .032	.137 ± .049	.28 ± .06	.43 ± .08	1.73 ± .23	1.02 ± .15
Garnet/Pyroxene	.09 ± .04	.55 ± .09	.40 ± .07	.30 ± .07	.51 ± .09	.51 ± .10
Zircon/Bl. gr. hbl.	.029 ± .016	.132 ± .047	.21 ± .05	.33 ± .06	2.12 ± .31	.94 ± .13
Garnet/Bl. gr. hbl.	.05 ± .02	.53 ± .09	.31 ± .06	.23 ± .05	.63 ± .12	.47 ± .09
Zircon/Green hbl.	.08 ± .05	.26 ± .09	.29 ± .06	.44 ± .08	2.36 ± .36	1.09 ± .16
Garnet/Green hbl.	.14 ± .06	1.04 ± .20	.42 ± .08	.31 ± .07	.70 ± .13	.55 ± .10
Zircon/Brown hbl.	.21 ± .12	.54 ± .19	1.13 ± .27	2.09 ± .58	6.1 ± 1.5	2.4 ± .5
Garnet/Brown hbl.	.36 ± .15	2.15 ± .54	1.63 ± .37	1.45 ± .41	1.79 ± .44	1.20 ± .26
Garnet/Zircon	1.7 ± .9	4.0 ± 1.3	1.44 ± .32	.70 ± .16	.29 ± .05	.50 ± .09

The sampling error (σ) of a ratio between two minerals is dependent on (1) the value of the ratio, and (2) the number of grains of the two mineral species that are counted (not on the total number of grains of all species counted). For the ratio A/B, σ may be calculated from the equation

$$\sigma_{A/B} = \pm \frac{\sqrt{\frac{A \cdot \sigma_B^2}{B} + \sigma_A^2}}{B}, \quad \text{(Mellor, 1926)}$$

where A and B are the number of grains of the two minerals that were counted, and σ_A and σ_B are their standard deviations as computed from the equation σ_A or $\sigma_B = \sqrt{npq} = \sqrt{A \cdot B/(A+B)}$.

The ratios and their standard deviations for seven selected minerals in three size grades of samples A and G are presented in Table 15. In this table, ratios between minerals of about the same specific gravity have been separated from ratios between minerals of different specific gravity. For minerals of about the same specific gravity, the difference between ratios exceeded the larger of the two standard devia-

tions for 9 of the 21 pairs (43 per cent); for minerals of differing specific gravity, for 39 of the 42 pairs (93 per cent).

To evaluate more accurately the effect of density and to determine whether the differences for the same and different density heavies were greater than those to be expected from chance errors of sampling, further calculations were made. For each pair of ratios, t was determined from the equation

$$t = (A/B - A'/B')/\sqrt{\sigma_{A/B}{}^2 + \sigma_{A'/B'}{}^2},$$[18]

where A and A' and B and B' are the numbers of the two minerals in the two samples. The probability that the difference could have occurred as a result of random sampling was found from table of t values.

Most of the differences between pairs of ratios could have occurred as a result of sampling, others could not. For each of the two density groups, however, t value of .82 should be exceeded 50 per cent of the time, and a t value of 2.9 should be exceeded 10 per cent of the time as a result of random sampling errors. For ratios between minerals of about the same density, $t = .82$ was exceeded 9 times in 21 (43 per cent) and $t = 2.9$ was exceeded 2 times in 21 (9.5 per cent). It may be concluded that differences in ratios between minerals of about the same density do not exceed those to be expected in random sampling. In contrast, for ratios between minerals of different density, $t = .82$ was exceeded 39 times in 42 (93 per cent) and $t = 2.9$ was exceeded 15 times in 42 (36 per cent). Differences in ratios between minerals of different density cannot be caused by errors of random sampling. An objective statistical measure of similarity or difference can be applied to some ratios but not to others, the critical factor being the difference in specific gravity of the minerals forming the ratio.

In a preceding section, the assumption was made, and later partially confirmed, that grains of hydraulic equivalent size are transported and deposited together. It also was shown that specific gravity and the hydraulic equivalent size of a mineral are closely related. If this is true, and if two minerals of about the same specific gravity, and therefore about the same hydraulic equivalent size, are being transported by a stream, deposition of one mineral will be accompanied by deposition of the other in the proportion in which they are being transported. The ratio between them will be constant, regardless of the absolute amount of both that is deposited at any place. In contrast, minerals of different specific gravity, and therefore differing hydraulic equivalent size, will not be deposited in the proportions in which they are transported, and, therefore, the ratios will differ as the hydraulic conditions at the site of deposit vary.

If this explanation is correct, ratios between minerals of about the same density should be the same, regardless of the average grain size and degree of sorting of the deposits in which they occur. Such ratios should be more widely applicable than any other number basis of comparing heavy minerals. Because ratios by number are

[18] Croxton and Cowden (1939), pp. 329-330, 875. Tables of t values may be found in most modern texts on statistics. For comparing two ratios, $n = 1$ and therefore the standard deviation and the standard error of each ratio are the same. Two degrees of freedom are used in determining the probabilities.

more easily obtained than hydraulic ratios, they should be used whenever possible in preference to hydraulic ratios. It should be clearly recognized, however, that such ratios by number do not give all available data for comparative purposes, since the weight of heavies as well as their proportion by number may vary. Clearly a correlation between deposits having similar ratios by number, but very different total weights of heavies, would be questionable. Also, as will be shown, ratios by number cannot be used to evaluate the relative importance of sediment sources.

For ratios between minerals of different density, it is very doubtful whether an objective measure of similarity or difference can be used, unless the average size and degree of sorting of the deposits is considerably less than that at Bosque. Such ratios are no more useful than number percentages and, like number percentages, may lead to invalid conclusions in some types of investigations. In considering the change in mineral composition with distance of transport, for example, a progressive change in ratio similar to that shown by the dashed line in Figure 9B might be obtained. This change would be due to change in hydraulic conditions, not to sorting, wear, or other factors. Similarly, if the ratio does not change, sorting or wear may have occurred but may have been compensated by changes caused by varying hydraulic conditions.

Same relative size grade.—For size grades having the same relative position with respect to the size distribution of the samples, data on ratios by number are not available from the Bosque investigation. It is known, however, that ratios by number between minerals of the same density measure the relative availability of the two minerals. If the relative availability changes with grain size, as it commonly does (Table 15), the ratios will reflect this difference in availability. When the difference in relative availability is large, ratios in closely related samples might appear to differ significantly. It seems reasonable to conclude that ratios between minerals in the same relative size grades will be more limited in applicability than ratios between minerals in the same size grades.

Entire sample.—Unfortunately, the extent to which ratios based on examination of entire samples may be used could not be determined by statistical tests of the Bosque data. Because the mineral composition in the entire samples was computed and not determined experimentally, the number of grains is not known, and the standard deviations cannot be estimated. Some comments are possible, however. As noted above, ratios by number between minerals of about the same density are measures of relative availability of the two minerals. If an entire sample is examined, the ratio will give an average relative availability for all sizes present. However, if the relative availability changes markedly with size (as for zircon at Bosque), a new factor is introduced. This factor becomes more important as the difference in average grain size and sorting of the samples increases. For some textural range, now unknown, an objective measure of similarity or difference cannot be used.

For ratios between heavies of different density, the examination of entire samples may reduce the variations due to hydraulic conditions and other factors for some textural ranges but may increase the variations for others. The usefulness of an objective measure for such ratios is questionable.

RATIOS BY WEIGHT

For minerals of about the same specific gravity, the ratios by weight in a size grade will be essentially the same as ratios by number. Therefore, for a size grade common to all samples number and weight ratios will have essentially the same advantages and disadvantages in comparing heavy-mineral compositions. Ratios by number, being more easily obtained, will be more widely used than ratios by weight.

For minerals of different specific gravity, the ratios by weight for a single size grade will not be the same as the ratios by number. Due to varying hydraulic conditions, inherent differences between the ratios by weight will be present. Consequently, an objective measure cannot be used to determine the statistical similarity or dissimilarity of samples.

In the same relative size grade, the ratios by weight will be the same as the ratios by number for minerals of the same density, but not for minerals of different densities. Ratios by weight will have the same advantages and disadvantages as ratios by number in the same relative size grades.

If entire samples are examined, there may be notable differences in the ratios by number and ratios by weight for minerals of the same density. Grains of large size may have almost no effect on the ratios by number but may be very important in determining the ratios by weight. Because the ratios by weight will measure the average relative availability of the two minerals in the entire sample, such ratios may be expected to have essentially the same advantages and disadvantages as ratios by number for entire samples.

WEIGHT PERCENTAGES

Same size grade.—In a single sample, weight percentages will be essentially the same as hydraulic ratios for those size grades that are on or just finer than the "straight section" of the light mineral cumulative curve. For two or more samples, the weight percentages will be essentially the same as the hydraulic ratios only in those size grades for which the light mineral cumulative curves of all samples are straight. In other size grades, the weight percentages will be too large or too small (Table 11), and the variations about these values will be large (Table 8). Therefore, in practice, weight percentages will be restricted to comparing one or two $\sqrt{2}$ size grades in suites of samples that have a narrow range in average grain size. If the use of weight percentages are not so restricted, misleading changes or differences in mineral composition of the type illustrated by Figure 9A may be obtained.

Where applicable, however, weight percentages have several advantages: (1) An objective measure of similarity or difference may be used, provided the standard deviation is increased by using the corrective factor C_s (Fig. 8); (2) samples having the same number frequencies but different absolute amounts of heavy minerals may be differentiated; (3) the relative importance of sediment sources may be evaluated quantitatively, an objective that cannot be attained with methods based on numbers.

Same relative size grade.—Like ratios by number or weight, and hydraulic ratios, weight percentages are measures of relative availability. But relative availability changes with grain size. Consequently, in comparing the same relative size grades of samples that differ greatly in texture, notably different weight percentages might be obtained, even if the samples actually are closely related. Because the change

in relative availability with size cannot be predicted in advance for a stream or formation, suitable corrections that will permit the application of a measure of similarity or dissimilarity cannot be made.

Entire sample.—Weight percentages for the entire sample will measure the average relative availability in the sample as a whole. For samples from the same source but of differing texture, these average relative availabilities may differ considerably. The use of weight percentages for entire samples must be restricted to comparing samples of about the same texture.

HYDRAULIC RATIOS

Hydraulic ratios are determined for the same size grades or smaller units within different samples, but not for the same relative size grades, or for the entire samples. Provided the estimated standard deviation of hydraulic ratios are increased by using the corrective factor C_z, the similarity or dissimilarity of samples may be determined by objective statistical measures.[14] For reasons now unknown, C_z is larger for heavy minerals of high density than for heavies of low density.

Because any of the six objectives set forth under Methods in Common Use may be attained through use of hydraulic ratios, such ratios appear to be of wider applicability than any other method of representing mineral compositions. In comparison with the most widely applicable method based on numbers—namely, ratios between minerals of about the same density in a size grade common to all samples—hydraulic ratios have the following advantages: (1) Samples having the same ratios by number but different absolute amounts of heavy minerals may be differentiated. (2) Data on all minerals—not just those of the same density—may be obtained. Thus, for objectives 1, 2, 3, 5, and 6, more information is provided. (3) If the hydraulic ratios are known for all size grades in which heavy minerals occur, the size distribution by weight of any heavy mineral may be computed for any sample of known or postulated size distribution. This should be of value in the discovery and exploitation of economically useful minerals (objective 6). (4) Accurate quantitative data may be obtained on the relative importance of sediment sources.

The fourth advantage merits further discussion. Below the junction of a tributary with a main stream, the mineral composition depends not only on the relative frequencies by number of the various heavies in the tributary and main stream sands but also on the absolute amounts of heavy minerals in the two sands. This may be illustrated by a simple example. Assume that sand *X* carries 10 per cent by weight of heavies, of which half is apatite and half is hornblende. Because both of these heavies have essentially the same density and shape, the number frequencies would be essentially the same—namely, apatite 50 per cent; hornblende, 50 per cent. Assume also that sand *Y* carries only 2 per cent by weight of heavies, of which one-tenth is apatite and nine-tenths is hornblende. The number frequencies would be apatite, 10 per cent; hornblende, 90 per cent. A mixture of equal quantities

[14] To determine the similarity or dissimilarity of two samples: (1) Compute C_s from the equation $C_s = \sqrt{npq}/np$ (or a graph giving C_s for a range of n and p values); (2) determine C_{hr} from Figure 8; (3) multiply the hydraulic ratio (hr) by C_{hr} to give the estimated standard deviation (σ_{hr}). Compute t from the equation $t = (hr - hr')/\sqrt{\sigma_{hr}^2 + \sigma_{hr'}^2}$. From a table of t values (Croxton and Cowden, 1939, p. 875) determine the probability (when n or df is 2) that the existing difference could be due to chance errors of sampling ($P = .05$ indicates the difference is significant; $P = .01$, highly significant).

of sands X and Y would actually yield a sand containing 6 per cent by weight of heavies, of which apatite would be about 43.3 per cent and hornblende would be 56.7 per cent by weight. Yet, if the amounts of X and Y needed to produce this mixture were computed from the number percentages alone, the apparent contribution would be 5 parts of X to 1 part of Y.

If ratios are used, two answers are possible, neither of which is correct; the apatite/hornblende ratio indicating 2.8 parts of X to 1 part of Y; the hornblende/apatite ratio indicating 25 parts of X to 1 part of Y. Actual differences in percentage by weight between some of the tributary and main stream sands in the Middle Rio Grande Valley show that the weight percentages in foregoing example are not extreme (Rittenhouse, 1943b; 1943c). In Krynine's (1937) use of heavy minerals to evaluate sediment sources, it was tacitly assumed that the weight of heavies from all sources was the same. For most investigations this assumption is not valid.

SUMMARY

(1) The heavy-mineral composition in six samples from a transverse cross section of the Rio Grande was studied quantitatively. The number percentages in the nonmagnetic separates of seven size grades of each sample were determined by identifying a total of 27,630 grains. From these number percentages and the weights of heavies in each size grade, the size distributions by weight of 12 heavies in each of the 6 samples were computed.

(2) The size distributions by weight of the heavy and light minerals vary systematically among samples.

(3) These systematic variations are caused by (1) varying hydraulic conditions at the places and times of deposition, (2) the hydraulic equivalent size of each heavy mineral, (3) the relative availability for deposit of each mineral, and (4) some factor or factors now unknown.

(4) The hydraulic equivalent sizes of 16 minerals were determined and found to range from .2ϕ to 1.0ϕ. Hydraulic equivalent size of a mineral appears to be closely related to its density. Shape appears to be of secondary importance.

(5) For most of the 16 minerals, the relative availability changes with size.

(6) The magnitude of the variation due to unknown factors was determined. These variations are much greater for high- than for low-density heavy minerals but do not differ with size of grain. Different proportions of suspended-load and bed-load sediment in the six samples studied may cause part or all of the unexplained variation. For low-density minerals, all or part of the unexplained variation may be caused by random errors of sampling.

(7) The magnitude of variations due to hydraulic conditions was determined. These variations are greater for high- than for low-density minerals and, in contrast to the unexplained variations, are greater for some size grades than for others.

(8) The hydraulic ratio is recommended as a new and widely applicable method of representing heavy-mineral compositions. The hydraulic ratio is the same in the stream load and in all deposits from the stream load.

(9) Changes in the hydraulic ratios due to wear, sorting, and other factors are discussed.

(10) Methods of representing heavy-mineral compositions are discussed and their

limitations outlined. Diagnostic minerals, scales of abundance, percentages by number, ratios by number, ratios by weight, weight percentages, and hydraulic ratios were considered. Analysis was made for mineral compositions in a size grade common to all samples, in the same relative size grade, and in entire samples.

(11) No single method of representing mineral compositions is best for all heavy-mineral problems. For each problem, the method that will yield the needed information with a minimum of time and effort should be selected. If the limitatons of various methods are not observed, however, invalid conclusions may be reached.

(12) Of the methods based on numbers of grains, ratios between heavies of about the same specific gravity in a size grade common to all samples appear to be most widely applicable. Using such ratios, the statistical similarity or dissimilarity of samples may be established by objective statistical measures. Percentages by number are probably no better than scales of abundance, because objective statistical measures can be used only when the range in average grain size and sorting is slight.

(13) The hydraulic ratio is more widely applicable than any other method based on weights and can be used to solve some problems for which no number method can be used. Using hydraulic ratios, the statistical similarity or dissimilarity of samples may be established.

(14) It is believed that the principles of heavy-mineral transportation and deposition, and the limitations of various methods in representing heavy-mineral compositions discussed in this paper, will be applicable with some modification to beach and dune sands. Hydraulic equivalent sizes in such deposits will probably not be the same as those in fluvial sediments.

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LOWER AND MIDDLE CAMBRIAN STRATIGRAPHY IN THE GREAT BASIN AREA

BY HARRY E. WHEELER

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ABSTRACT

Biostratigraphic and lithologic correlations of Lower and Middle Cambrian strata are made in eastern and southeastern Nevada at Eureka, Cave Valley, Pioche, Delamar, Mormon Range, and Virgin Mountains, and in Arizona at the western end of the Grand Canyon near Grand Wash Cliffs, and in the Granite Gorge area of the Canyon.

These correlations, together with others in the better-known areas of Lower and Middle Cambrian strata in central Arizona, western Utah, and southeastern Idaho, disclose widespread faunal and lithogenetic continuity over a large part of the Great Basin area of the Southern Cordilleran geosyncline and thus permit unification and consequent simplification of formational nomenclature.

The Prospect Mountain quartzite (Eureka district, Nevada) is present throughout the entire region, ranging from Upper Algonkian (?) and Lower Cambrian in eastern Nevada and western Utah to lower Middle Cambrian in northwestern Arizona (Granite Gorge), central Arizona, northwestern Utah, and southeastern Idaho. The quartzite has been locally designated as Tapeats sandstone, Tintic, and Brigham quartzites.

The overlying Pioche shale (Pioche district, Nevada) is recognized from Eureka to western Grand Canyon and eastward throughout most of western Utah. In southeastern Nevada and northwesternmost Arizona the Pioche has previously been regarded as part of the Bright Angel shale; and in western Utah it has been called Ophir and Cabin. The Pioche formation is both Lower and Middle Cambrian over most of the Great Basin area but is Lower Cambrian at Eureka and Cave Valley (?), Nevada, and in the House and Deep Creek (?) ranges of western Utah, and Middle Cambrian in the Tintic and Sheeprock ranges of central Utah.

The Middle Cambrian Lyndon limestone and Chisholm shale (both of the Pioche district) may be traced northward to Cave Valley and southward to western Grand Canyon. Farther east in the Grand Canyon, the Lyndon limestone disappears, and the combined Pioche and Chisholm shales constitute the Bright Angel shale.

The Peasley and Burrows limestones and portions of the Highland Peak limestone are recognized at Cave Valley and Delamar in eastern Nevada as well as in their type area, the Pioche district, and the first of these is traced southward to western Grand Canyon.

INTRODUCTION

GENERAL STATEMENT

Original investigations of the Cambrian sequences in the Eureka and Pioche mining districts in Nevada (Wheeler and Lemmon, 1939; Wheeler, 1940) and other similar investigations of Cambrian stratigraphy in the Great Basin area contribute directly to the study of ore deposits, not only because certain stratigraphic units are evidently most amenable to replacement mineralization, but also because complex structural relationships prevalent in the mineralized areas require positive identification of the stratigraphic position of every rock unit.

As illustrated by Schenck (1940), integration of the stratigraphy of the Highland Peak limestone of the Pioche district (Wheeler and Lemmon, 1939) provided the data necessary for the operators of Bristol Silver mine to ascertain the stratigraphic position of the mine workings. With this information, a winze was sunk from the lowest workings in search of a known potential ore-bearing limestone, which, when encountered, contained an excellent ore body.

Appreciable mineralization occurs in Cambrian strata at Eureka, Pioche, Delamar, Cave Valley, Tybo, Groom, Cherry Creek, and Snake Range in Nevada, and Cottonwood, Tintic, and Ophir in central Utah. At points as widely separated as Pioche and Little Cottonwood (230 miles) replacement bodies are found in limestone beds of the Pioche shale.

Not only should the present widespread formational correlations and nomenclatural simplifications be of benefit in interpreting and interpolating local relationships in mining districts, but it should also provide a better basis for a more thorough understanding of regional Cambrian biostratigraphy, sedimentation, and paleogeography throughout the entire Great Basin area. In this regard, however, it is the writer's opinion that many additional data on lithogenetic relationships are needed, especially from western and southern Nevada, before satisfactory conclusions for the entire region can be reached.

The purpose at present, therefore, is to present only lithogenetic and time-stratigraphic correlations within those portions of the Great Basin area for which data are now adequate. The most extensive formational correlations involve only the most widespread and detrital portion of the sequence, the Prospect Mountain and Pioche formations. Other units are correlated from eastern Nevada to northwestern Arizona. Present knowledge of the limestone-dolomite succession above the Pioche shale is insufficient to permit formational correlations between eastern Nevada and western Utah.

LOCATION OF AREA

The region covered by the correlation of the detailed Lower and Middle Cambrian sections shown in Plate 1 extends from Eureka, in east-central Nevada (39° 30′ N. and 116° W.), southward 260 miles through eastern and southeastern Nevada to

western Grand Canyon in northwestern Arizona (36° 10′ N. and 114° W.), and thence eastward for 125 miles to Nankoweap Valley in the Granite Gorge region of the Grand Canyon (36° 15′ N. and 111° 50′ W.).

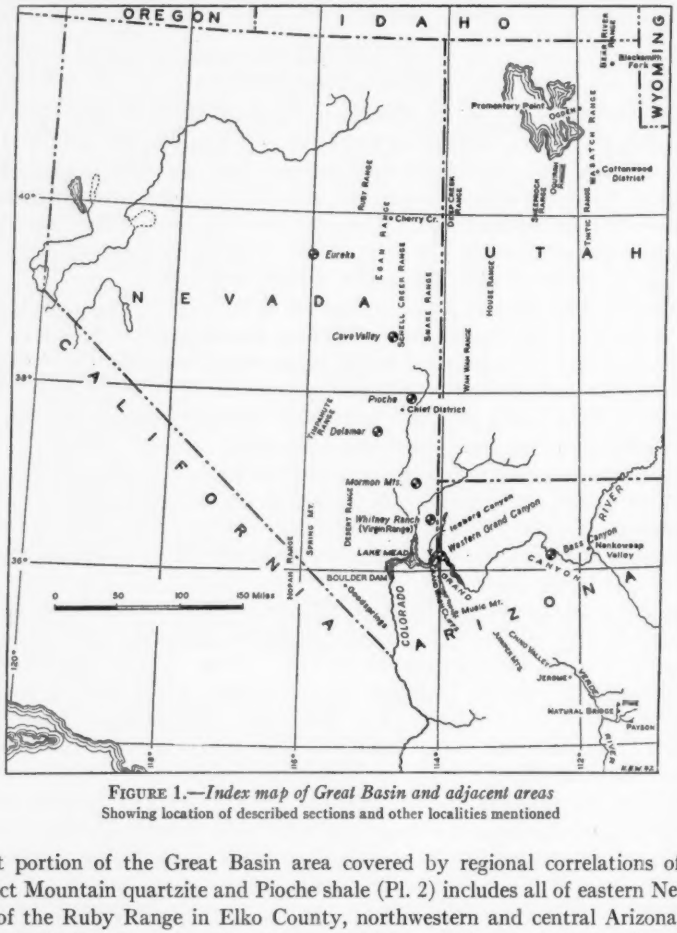

FIGURE 1.—*Index map of Great Basin and adjacent areas*
Showing location of described sections and other localities mentioned

That portion of the Great Basin area covered by regional correlations of the Prospect Mountain quartzite and Pioche shale (Pl. 2) includes all of eastern Nevada south of the Ruby Range in Elko County, northwestern and central Arizona, the western half of Utah, and southeasternmost Idaho. This area is enclosed between parallels 34° and 42° 30′ and meridians 111° and 116°, an area approximately 600 miles long and more than 250 miles wide.

Except for the absence of formational correlations in southwestern Nevada and southern California, the correlations presented in this report extend virtually throughout the entire "Great Basin area" of the southern Cordilleran geosyncline, as defined by Schuchert (1910) and illustrated by Deiss (1941). (*See* Figure 1.)

FIELD WORK

In addition to the field work for the discussions of the Cambrian successions of the Eureka and Pioche districts (Wheeler and Lemmon, 1939; Wheeler, 1940), the writer has made the following field studies:

A brief examination of the Cambrian sequence on the north wall of the Grand Canyon at Bright Angel Canyon, in June 1936.

Collection of fossils in western Grand Canyon and preparation of a cross section of the Cambrian on Grand Wash Cliffs about 20 miles south of Lake Mead in December 1938 in company with Edward T. Schenk and Dwight M. Lemmon.

Additional work in the Pioche district during May and June of the years 1940, 1941, and 1942.

Early in November 1940, in co-operation with Edward T. Schenk and in company with Dudley L. Davis, sections were measured in western Grand Canyon and the Mormon Range, and later Davis and the writer visited the Virgin Range, Delamar, and Cave Valley and measured sections at the last two.

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EUREKA DISTRICT, NEVADA

GENERAL CONSIDERATIONS

One of the several classic areas of Cambrian rocks in western America is the Eureka mining district of east-central Nevada. Since its original treatment by Hague (1883; 1892) the formational sequence has been much confused and disputed, partly because of failure to detect fault contacts between fossiliferous formations of similar lithologic character (*e.g.*, Secret Canyon and Dunderberg shales), and partly because the Hamburg and Dunderberg formations have been interpreted as repetitions by thrust faulting of the Eldorado and Secret Canyon formations. As a result of these structural misinterpretations several original faunal allocations and many reallocations by Walcott (1925) and Resser (1935, *et seq.*) are incorrect. The Dunderberg shale faunas have been assigned to the Secret Canyon shale, whereas the Secret Canyon faunas have been allocated to the unfossiliferous Eldorado limestone.

Wheeler and Lemmon (1939) believe they have overcome most of the stratigraphic difficulties of the Eureka Cambrian by preparing detailed sections in areas with less severe deformation and by placing faunules from published fossil localities on a carefully prepared geologic map.

It is now possible to make both lithologic and faunal correlations between the Cambrian sequence at Eureka and the Cambrian successions of other Cordilleran areas[1].

PROSPECT MOUNTAIN QUARTZITE

The basal Cambrian formation in the Eureka district is the Prospect Mountain quartzite (Hague, 1883) the type area being on the west slope of Prospect Mountain about 5 miles south of Eureka. The formation consists mostly of reddish-brown, highly fractured quartzite with occasional intercalations of quartzitic conglomerate and some thin beds of micaceous shale. Wheeler and Lemmon (1939) measured 1660 feet in the type area, but the base is not exposed, and the 200 feet of argillaceous beds at the top is assigned to the Pioche shale; thus the estimated exposed thickness of the Prospect Mountain is 1460 feet.

The exposed part of the Prospect Mountain quartzite at Eureka is Lower Cambrian, since the strata are immediately overlain by the *Olenellus*-bearing Pioche shale. However, if the thickness is appreciably greater than the exposed 1460 feet, as in some areas in the Southwest, sedimentation may have begun before Cambrian time.

PIOCHE SHALE

About 500 feet east of the summit of Prospect Mountain, some 200 feet of fossiliferous, calcareous, micaceous shale, sandstone, and quartzite with a few intercalations of dark-gray limestone conformably overlie the quartzites. The limestone strata range from a few inches to 2 feet. In the absence of data on the Pioche shale between its type section and Eureka, Wheeler and Lemmon (1939) regarded these more argillaceous beds as topmost Prospect Mountain, although the partial age equivalence of the two shales was noted. More recently the sequence has been examined in the intervening Cave Valley district where the Pioche shale has an intermediate thickness. Therefore, in view of the known thinning of the Pioche shale northward from its type section, it is concluded that the shales exposed on Prospect Mountain are lithogenetically equivalent to the Pioche formation.

The presence of *Olenellus* cf. *fremonti* Walcott and *O. gilberti* Meek in the upper half of the Pioche at Eureka indicates that the shale belongs entirely to the Lower Cambrian series.

ELDORADO LIMESTONE

The calcareous rocks constituting most of the eastern slope of Prospect Mountain were originally designated as Prospect Mountain limestone by Hague but renamed Eldorado limestone by Walcott (1908b). Wheeler and Lemmon (1939) excluded the upper, thinly bedded, dark limestones, naming them the Geddes formation. The

[1] A good case in point is the correlation of the type Pogonip limestone of the Hamilton district, Nevada currently being prepared by Mr. Samuel Holliday of the Stanolind Oil Co., Houston, Texas. Until these faunal re-allocations were considered, the Upper Cambrian lithologic and faunal correlations between Hamilton and Eureka were not accordant.

restricted Eldorado consists of an estimated[2] 2000 feet of thickly bedded to massive, light-colored, secondary dolomite and limestone.

No diagnostic fossils are known from the Eldorado formation. Those reported from the "Mountain shale" member by Hague and Walcott are actually from infaulted segments of Secret Canyon shale. Since the Eldorado is apparently conformable on the *Olenellus*-bearing Pioche shale, and below the Middle Cambrian Geddes limestone, it is regarded as ranging from Lower to Middle Cambrian.

GEDDES LIMESTONE

In his original description of the Eldorado limestone, Hague referred to the uppermost 335 feet as the "stratified limestone." In recent years this unit has been called the "blue flaggy" limestone. Wheeler and Lemmon (1939) proposed that these distinctive, dark-gray, carbonaceous, thinly bedded limestones be named Geddes, from the Geddes and Bertrand mine in Secret Canyon, the main adit of which transects the formation.

The precise age of the Geddes limestone has not been established, but on stratigraphic position, Wheeler and Lemmon tentatively assigned this formation to the early medial Cambrian, though it seems a little younger. Walcott (1884, p. 45) gives the locality of "*Dicellocephalus ? expansus*" = *Olenoides expansus* as "Prospect Mountain limestone at base of Secret Canyon shale, in New York Cañon. . . ." This occurrence of *Olenoides*, and the presence of *Elrathia occidentalis* (Walcott) and *Kootenia eurekensis* Resser near the base of the immediately overlying Secret Canyon shale, strongly suggest that the Geddes limestone belongs fairly high in the Middle Cambrian. In this regard, *Agnostus richmondensis* Walcott from the Geddes formation on the 700-foot level of the Richmond mine on Ruby Hill should be re-examined. The Geddes occupies a stratigraphic position (Pl. 1) comparable to the lower part of the Highland Peak limestone of Pioche, which has been designated as upper Middle Cambrian (Wheeler, 1940, p. 33).

SECRET CANYON SHALE

The Secret Canyon shale, described by Hague, has a measured thickness of 1035 feet (Wheeler and Lemmon, 1939). The lower half is very thin, papery, argillaceous shale with a few thin interbedded limestones; the upper is thinly and irregularly bedded platy limestone with shale partings. It seems conformable with the underlying Geddes formation and the overlying Hamburg limestone.

Some of the fossils collected by Walcott (1884) have been reallocated in accordance with procedure described above. From the lower part of the formation Walcott collected *Elrathia occidentalis* (Walcott) and *Kootenia eurekensis* Resser; the upper beds have yielded *Ehmania oweni* (Walcott), *Eldoradia lata* Resser, *E. linnarssoni* (Walcott), *E. prospectensis* (Walcott), *Eteraspis laeviceps* (Walcott), and *Holteria problematica* (Walcott). These fossils date the Secret Canyon as upper Middle Cambrian.

The exact position of the Middle-Upper Cambrian boundary in the Eureka district is not known. The Geddes and Secret Canyon formations are upper Middle

[2] Internal faulting precludes the possibility of accurate measurement.

Cambrian; the overlying, secondarily dolomitized Hamburg limestone is unfossiliferous, and the Dunderberg shale above carries late Upper Cambrian fossils (Wheeler and Lemmon, 1939, p. 27). Since the Hamburg appears to be lower Upper Cambrian, the writer follows Wheeler and Lemmon in tentatively placing the Middle-Upper Cambrian boundary at the top of the Secret Canyon shale. Regional correlation is not attempted in the present paper.

PIOCHE DISTRICT, NEVADA

GENERAL CONSIDERATIONS

The Cambrian sequence of the Pioche district (Fig. 2) is among the thickest and most complete of those studied in detail in the Cordilleran region. The early Paleozoic stratigraphy of the district has received more attention than in most Nevada areas because of the significance of sedimentary relationships in the occurrences of the lead, zinc, manganese, and silver deposits, and because the intricate fault patterns in mineralized areas cannot be disentangled without detailed knowledge of the stratigraphic sequence. The Cambrian at Pioche totals at least 9500 feet. The Lower and Middle Cambrian portions have been studied in much the greatest detail; the Upper Cambrian Mendha formation is notably poorly integrated.

PROSPECT MOUNTAIN QUARTZITE

The basal quartzites of the Pioche district Cambrian sequence were identified by Spurr (1903, p. 41) and Westgate (1927; 1932) as the Prospect Mountain formation on lithology and stratigraphic position.

The formation, described by Westgate (1932), consists of red to buff and white, generally thick-bedded to massive, sometimes cross-bedded quartzite, with minor interbedded conglomerate and shale. Shales are intercalated in the thinly bedded uppermost strata which grade into the overlying Pioche shale.

As at Eureka, the base of the quartzite is not exposed. The exposed portion has been estimated as 1500 feet thick by Westgate and 2000 feet by Wheeler and Lemmon. The upper part of the Prospect Mountain in this district is Lower Cambrian, for the top lies only 250 feet below the *Olenellus* fauna of the lower Pioche shale. Nevertheless, in the Pioche district, as perhaps at Eureka, an unknown portion of the formation may have accumulated prior to Cambrian time.

PIOCHE SHALE

Conformably overlying the Prospect Mountain quartzite are greenish-yellow, buff, and brown, micaceous shales containing a moderate amount of intercalated sandstone, quartzite, and limestone, named the Pioche shale by Walcott (1908a). He assigned the formation to the Lower Cambrian, but Burling (1914) stated that it contains both Lower and Middle Cambrian faunas. Westgate (1932), who prepared the first detailed section of the shale, measured its thickness in the Highland Range as 1120 feet and assigned it all to the Lower Cambrian, following Walcott.

Deiss (1938) remeasured the Highland Range section as 970 feet thick; after study of the faunas, he restricted the term Pioche to the Lower Cambrian portion (lower 600 feet) and applied the name Comet shale to the Middle Cambrian part (upper 370 feet). Because they believed the splitting of the Pioche shale unjustified litho-

logically, and not in accordance with the recommendations of the Committee on Stratigraphic Nomenclature (Ashley *et al.*, 1933, p. 431), Wheeler and Lemmon (1939) rejected the term Comet and restored the name Pioche to its original status. As shown in the present paper, the Pioche formation, as originally defined, is present over a vast area in eastern and southeastern Nevada, northern Arizona, and western Utah as an easily recognizable and mappable lithogenetic unit. The Comet and restricted Pioche of Deiss are not valid lithogenetic or cartographic units, even within the Pioche mining district.

Among those Pioche shale fossils listed by Deiss, *Olenellus gilberti ?* Meek and *Zacanthoides levis* (Walcott) from the "Combined Metals bed" about 250 feet above the base date the lower part of the formation as Early Cambrian. *Kochaspis augusta* (Walcott) and *K. liliana* (Walcott), from 600 feet above the base, and *Albertella* sp. and *Kootenia* sp. from near the top place the upper part of the shale in the lower Middle Cambrian in the Pioche district.

LYNDON LIMESTONE

Westgate (1927; 1932) measured 400 feet of limestone conformably above the Pioche shale along the spur south of Peasley Canyon on the west side of the Highland Range and named it the Lyndon limestone. On the spur north of Lyndon Gulch, about a mile south of Westgate's section, Deiss (1938) measured 345 feet of Lyndon, which agrees with the writer's estimate of 350 feet in the Ely Range about 8 miles eastward.

The Lyndon formation may be subdivided into four members[3]: (1) a lower 170-foot member of dark-gray, fine- to medium-grained, thick-bedded limestone; (2) a 50-foot member of light-gray to nearly white, fine-grained to dense, thick-bedded to massive limestone; (3) a 90-foot member of limestones similar to the underlying, interbedded with some medium- to dark-gray strata, members 2 and 3 being separated by a zone of iron-stained arenaceous and argillaceous limestones; and (4) a topmost 34-foot member of dark-gray, fine- to medium-grained, thinly and distinctly bedded limestones.

No diagnostic fossils have been found in the Lyndon formation. It is early Medial Cambrian, however, since it lies between the *Albertella* biozone of upper Pioche shale and the *Zacanthoides-Anoria* fauna of the Chisholm shale.

CHISHOLM SHALE

Walcott (1916) described an estimated 100 feet of argillaceous rocks from Half Moon Gulch in the Ely range near Pioche as the Chisholm shale. It is yellow-buff to brown, fine-grained micaceous shale with a few intercalated gray to olive-drab limestones ranging from a few inches to about 2 feet thick. The Chisholm measures about 75–100 feet in the Ely Range, 137 feet at Lyndon Gulch in the Highland Range, and 180 feet at Klondike Gap in the Chief Range about 10 miles to the south.

The following species have been listed from the Pioche district: *Eocystites ? longidactylus* Walcott, *Alokistocare packi* Resser, *Alokistocare piochensis* (Walcott),

[3] Thicknesses given are from Highland Range modified after Deiss (1938).

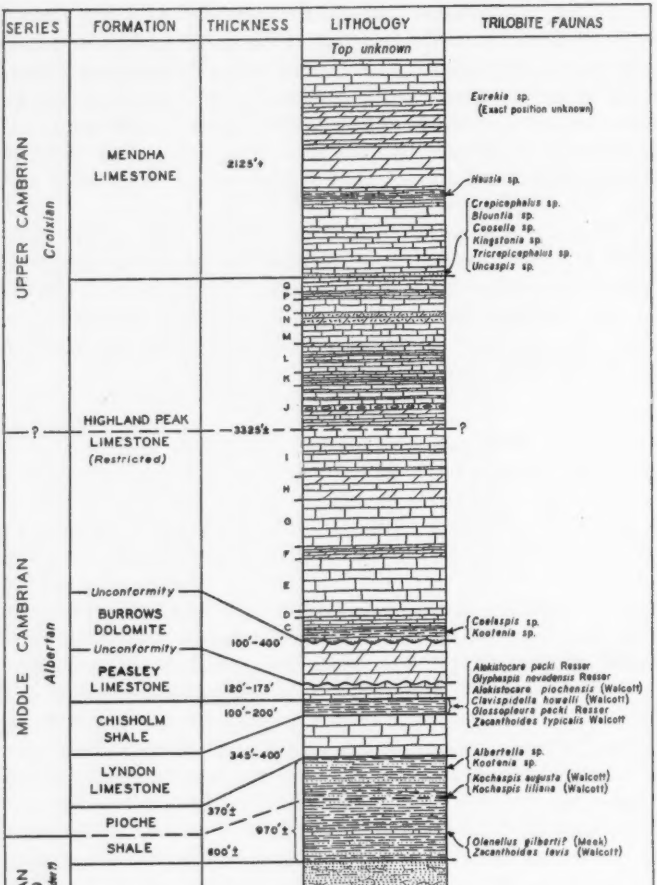


FIGURE 2.—*Cambrian columnar section of Pioche district, Nevada*

Clavispidella howelli (Walcott), *Glossopleura packi* Resser, *Glyphaspis nevadensis* Resser, and *Zacanthoides typicalis* Walcott. This fauna clearly indicates an early Medial Cambrian or Bonnetian age.

PEASLEY LIMESTONE

Westgate (1927) proposed the name Highland Peak limestone for nearly 4000 feet of limestones and dolomites directly overlying the Chisholm shale. Wheeler and Lemmon (1939) integrated the various partial sections of the Highland Peak and divided it into 17 cartographic units (A to Q). On discovering two unconformities, Wheeler (1940) removed units A and B from the Highland Peak and defined them as the Peasley limestone and Burrows "dolomite." Wheeler (1941) rejected the name Peasley for the term Muav from the Grand Canyon section, believing the two formations to be lithogenetically equal, but later work has proved the need for distinction. Thus the name Peasley is restored in the Pioche district and adjacent regions.

The Peasley limestone, conformable on the Chisholm shale, consists mostly of a variable thickness of dark-gray, medium-grained, thickly bedded to massive limestone. Weathered surfaces are often dull gray and rough, showing irregular banding or mottling in zones of intercalated impurities; thin irregular strata are dolomitized locally.

In its type section in the Highland Range the Peasley is 120 feet thick; in the Ely Range it ranges from 100 to about 160 feet, depending upon the amount of post-Peasley and pre-Burrows erosion.

The Peasley lies above the lower Middle Cambrian Chisholm shale and is separated by several hundred feet of strata and two unconformities from the upper Middle Cambrian faunas of the lower Highland Peak limestone.

BURROWS LIMESTONE

Throughout the Pioche district and adjacent territory at least, the Peasley limestone is unconformably overlain by the Burrows limestone. Wheeler (1940) described the Burrows as a dolomite because the many occurrences known at that time were preponderantly of epigenetic or secondary dolomite. Observation of the Burrows at widely scattered localities in southeastern Nevada indicates that the original fine-grained to dense, massive limestone phase is as common as the dolomite phase, even more common in areas of little faulting and mineralization. Therefore the term denoting the original character of the formation seems most appropriate.

Most of the Burrows formation is light gray and massive. The basal 30 feet, however, is thinly bedded ($\frac{1}{2}$ to 2 inches) and variegated. Thickness of the Burrows in the district is decidedly variable, depending upon the local extent of the post-Burrows–pre-Highland Peak degradation. It is 400 feet at the type section in the Highland Range, about 230 feet in the Ely Range near Pioche, and 130 feet at the southern extremity of the Ely Range near Panaca.

The Burrows limestone lies somewhere near the middle part of the Middle Cambrian. It is separated from the *Zacanthoides* biozone of the Chisholm shale by an unconformity and the Peasley limestone, while it is unconformably overlain by the Highland Peak limestone which carries a late Medial Cambrian fauna about 60 feet above the base.

HIGHLAND PEAK LIMESTONE

Westgate (1927) proposed the name Highland Peak for nearly 4000 feet of limestones and dolomites overlying the Chisholm shale and underlying the Upper Cambrian Mendha formation. He estimated its thickness at 3000 feet and stated that the entire sequence could not be worked out because of lack of good guide horizons. Wheeler and Lemmon (1939) integrated the formation, described 17 cartographic subdivisions, and presented a composite thickness of 4080 feet for the Highland Peak in the Pioche district. Wheeler (1940) emended the thicknesses of a few subdivisions, described the unconformities, defined the Peasley and Burrows formations (thus restricting the Highland Peak), and first listed the fauna from this thick sequence. The thickness of the revised Highland Peak formation in the district is 3325 feet.

In a thin, shaly member about 60 feet above the base of the restricted Highland Peak limestone *Coelaspis* sp. and *Kootenia* sp. are listed, with undescribed genera, suggesting that the lower part of the formation is Upper Middle Cambrian. Since the basal beds of the Mendha limestone, apparently conformable on the Highland Peak, contain *Blountia* sp., *Coosella* sp., *Kingstonia* sp., *Tricrepicephalus* sp., and *Uncaspis* sp. (lower Upper Cambrian), the Middle-Upper Cambrian boundary is somewhere within the Highland Peak formation. The series boundary is questionably and arbitrarily placed at the base of unit J, a little above the midpoint of the formation (Pl. 1).

WESTERN GRAND CANYON, ARIZONA

GENERAL CONSIDERATIONS

Among the most important Cambrian sections for interregional correlation in the Southwest is that exposed in western Grand Canyon near Grand Wash Cliffs. This occurrence, at the western edge of the Colorado Plateau, links the Cambrian formations of that physiographic province with those of the Basin and Range region. This section is also critical with respect to the east-west extent of certain units which change lithology as they approach the eastern shore of the Cambrian Cordilleran geosyncline. The Cambrian in western Grand Canyon is lithologically and faunally very similar to the classic sequence at Pioche.

PROSPECT MOUNTAIN QUARTZITE

The basal Cambrian sediments of western Grand Canyon rest with marked unconformity on pre-Cambrian granite gneiss assigned to the Archean (Campbell and Maxson, 1938). These reddish-brown through buff to cream strata consist mostly of coarsely granular, somewhat feldspathic and glauconitic, and mostly cross-laminated (McKee, 1940) quartzites and sandstones. The lower 118 feet is massive, whereas the upper 61 feet is thin-bedded with shale intercalations.

Gilbert (1875) referred these quartzites and the overlying shales to the Tonto group which he had defined farther east in the Grand Canyon. R. B. Wheeler and Kerr (1936) recognized the quartzite as the lithogenetic counterpart of the Tapeats sandstone of Noble (1914) in the Granite Gorge area of the Grand Canyon. Schenk and Wheeler (1941) identify these arenaceous sediments with the Prospect Mountain quartzite of Eureka, Nevada.

The Prospect Mountain formation has been recognized in the Ruby Range (Sharp, 1942), in the Egan Range (Hill, 1916, p. 24; Schrader, 1931b), at Pioche (Walcott, 1886, p. 36; Westgate, 1927), in the Chief district (Callaghan, 1936), at Delamar (Callaghan, 1937), and in the Timpahute Range (Walcott, 1886; Spurr, 1903), all in Nevada. In western Utah this formation has been recognized in the House Range (Walcott, 1908a; Deiss, 1938) and in the Gold Hill quadrangle (Nolan, 1935). It is also here reported at Cave Valley and in the Mormon and Virgin ranges in southeastern Nevada, from the Granite Gorge region of the Grand Canyon southward into central Arizona, and throughout western Utah and southeastern Idaho. It occurs also in the Mount Wheeler area of the Sanke Range and portions of the Schell Creek Range.

Although these quartzites are identical with the Tapeats formation farther east in the Canyon, the name Prospect Mountain has been selected on priority and in the interest of simplification of formational nomenclature.

In the western Grand Canyon this 179-foot sequence is conformable beneath the Pioche shale which carries the *Olenellus* fauna about 13 feet above its base. The entire quartzite formation in this area, therefore, is assigned to the Lower Cambrian or Waucobian. The basement rocks and most of the Prospect Mountain formation are submerged in Lake Mead in the extreme western end of the Grand Canyon. However, the formation may still be seen in approximately the same stratigraphic relationships in Iceberg Canyon about 8 miles west of Grand Wash Cliffs and along the cliffs about 16 miles south of the Canyon.

PIOCHE SHALE

Gilbert (1875) recognized the Tonto shale in western Grand Canyon, and R. B. Wheeler and Kerr (1936) referred the argillaceous strata above the quartzite to the Bright Angel shale (Noble, 1914) of the Granite Gorge region. Schenk and Wheeler (1942) have agreed that the lithogenetic counterpart of the Bright Angel formation is present in western Grand Canyon but that, since its equivalent in the Pioche district has been subdivided into the Pioche, Lyndon, and Chisholm formations, these units should be recognized wherever they may be distinguished. The present paper demonstrates that these three formations are lithologically, stratigraphically, and faunally traceable from Pioche to the Canyon via Delamar, the Mormon Range, and Virgin Mountains. Therefore the Pioche shale originally defined by Walcott (1908a), consists in western Grand Canyon of 304 feet of chocolate to red-brown, buff and pale-green, micaceous shales and sandstones.

As in the type area, the Pioche formation here is both Lower and Middle Cambrian. The position of the series boundary is uncertain. The Lower Cambrian genus *Olenellus* is found about 13 feet above the base, and a species of *Albertella* (lower Middle Cambrian) occurs 31 feet below the top. In addition, E. D. McKee collected a specimen identified as the lower Middle Cambrian genus *Anoria* from beds 73 feet below the top of the Pioche shale in this section. This limits the series boundary and also is of interest because *Albertella* is normally found below *Anoria*.

Schenk and Wheeler (1942) have provisionally and questionably placed the Lower-Middle Cambrian boundary at the top of the dark-maroon sandstone 186 feet above the base of the Pioche shale.

LYNDON FORMATION

Units "b", "c", and "d" of the "Tonto shale" briefly described by Gilbert (1875) consist of a lower, 12-foot member of rust-colored, impure, massive dolomite; a middle, 40-foot member of shale, sandstone, and dolomite; and an upper, 18-foot dolomite bed identical in appearance to the basal layer. This 70 feet of mostly calcareous rocks is conformable on the Pioche shale and accordant beneath shale of the Chisholm formation.

Although much thinner than the Lyndon limestone (345 feet) at its type locality on the west side of the Highland Range in the Pioche district, and though mostly dolomite with some clastic material rather than all limestone, it is nevertheless stratigraphically and faunally identifiable as the Lyndon. The near lithogenetic identity is apparent also if the dolomites are epigenetic (Schenk and Wheeler, 1942).

The Lyndon formation has yielded no diagnostic fossils. Its conformable position between the Pioche and Chisholm shales, both of which are lower Middle Cambrian, clearly places it within the lower Middle Cambrian series at both its type locality and in western Grand Canyon. The presence of *Albertella* 31 feet below the base of the Lyndon, and of *Glossopleura* and *Anoria* in the overlying Chisholm shale, clearly indicates the Bonnetian stage as the time-stratigraphic position.

CHISHOLM SHALE

The uppermost of the three formations constituting the lithogenetic counterpart of the Bright Angel shale in the western Grand Canyon area is composed largely of maroon-red, dark-brown, and dark-green shales, measuring about 99 feet (Schenk and Wheeler, 1942). These carry typical Chisholm trilobites, including the species *Alokistocare althea* Walcott, *Anoria* n. sp., *Clavispidella enucleata* Resser, *Elrathia* sp., *Glosspleura mckeei* Resser, and *Glyphaspis* sp. *Zacanthoides* is the only genus characteristic of the Chisholm shale in its type area not present in this fauna. The Chisholm shale in this vicinity belongs to the lower Middle Cambrian *Glossopleura* biozone.

PEASLEY LIMESTONE

R. B. Wheeler and Kerr (1936), Schenk and Wheeler (1941), and Wheeler (1941) all assigned the limestones above the Chisholm shale in western Grand Canyon to the Muav formation (Noble, 1941) of the Granite Gorge region farther east. However, Schenk and Wheeler (1942) state that McKee traced the upper strata of the type Muav limestone westward into western Grand Canyon where they disconformably overlie limestones (Mead formation) which in turn rest disconformably upon strata lithogenetically equal to the lower type Muav. Thus, if the Muav formation is traced westward from the type section to western Grand Canyon, part would lie above and another part below the Mead formation. Therefore, west of the eastern limit of the Mead formation the divided equivalents of the Muav limestone must be designated separately. Since the lower part of this limestone sequence has been named Peasley (Wheeler, 1940) in the Pioche district, and since it is continuous from Pioche to western Grand Canyon, Schenk and Wheeler have applied the name to the strata above the Chisholm shale in the western Canyon area.

The Peasley limestone consists of three massive, cliff-forming limestones separated

and overlain by slope-forming, thin-bedded shales, sandstones, and limestones, totaling about 400 feet. The massive limestones are medium to dark gray, fine-grained, with numerous dark-brown, irregular, silty or arenaceous laminae etched in relief on weathered surfaces.

Near the base of the formation are *Hyolithes* sp., *Alokistocare* sp., *Chancelloria* cf. *eros* Walcott, *Glossopleura* sp., and *Kootenia* sp. Near the middle occur *Hyolithes* sp. and *Elrathia* n. sp. The upper beds carry new species of the genera *Elrathia*, *Kootenia*, and *Solenopleurella*. These assemblages all appear to belong to the lower Middle Cambrian *Glossopleura-Kootenia* zone.

MEAD LIMESTONE

A variable thickness of almost white, to pale-pink and light gray, fine-grained, somewhat mottled, massive limestone lies disconformably upon the Peasley formation in western Grand Canyon. These rocks fit the description of the undolomitized phase of the Burrows limestone (Wheeler, 1940) of the Pioche district in lithology, stratigraphic position, and disconformable relations (Schenk and Wheeler, 1942). Because the Burrows has not been recognized in the southern half of the intervening distance between Pioche and the Grand Canyon, the strata in the Lake Mead region were designated as the Mead limestone. The Mead formation measures 110 feet at its type locality, but post-Mead erosion makes its thickness quite variable in the region. In fact, it is completely removed a few miles southeastward up the canyon.

Schenk and Wheeler (1942) state that in the absence of fossils the age of the Mead limestone is not determinable. They add that it is certainly Medial Cambrian if it is the equivalent of the Burrows limestone of Pioche. Farther east in the Grand Canyon, E. D. McKee (personal communication) has found specimens of *Asaphiscus* and *Solenopleurella* in beds of the Muav limestone which are younger than those overlying the Mead limestone in western Grand Canyon. Therefore, the Mead formation is older than these Medial Cambrian genera, and younger than the early Medial Cambrian Peasley limestone.

POST-MEAD LIMESTONES AND DOLOMITES

Schenk and Wheeler (1942) briefly describe the thick limestones and dolomites disconformably above the Mead limestone, which are in turn covered by Mississippian limestones. They show that the upper part of this undifferentiated sequence is Devonian, but that the lower portion may be Cambrian.

The paleontologic evidence from the Muav limestone indicates that some of the strata above the Mead are Medial Cambrian. The Cambrian-Devonian boundary is not yet established in western Grand Canyon.

GRANITE GORGE AREA (GRAND CANYON, ARIZONA)

GENERAL STATEMENT

Noble (1914) revised the Cambrian Tonto group (Gilbert, 1874; 1875), naming the Tapeats, Bright Angel, and Muav formations. The best known stratigraphic section of the Granite Gorge area of the Grand Canyon was prepared by Noble (1922) at Bass Trail on the south wall of the canyon. Formational thicknesses and relationships shown in Plate 1 are taken from the Bass Canyon section. Because

of its comparative detail and central location, this section may be regarded as typical for the area. The following data on the sequence and relationships, however, are taken from various described sections in the region.

PROSPECT MOUNTAIN FORMATION ("TAPEATS SANDSTONE")

The basal Cambrian strata at Bass Canyon, as described by Noble (1922), consist of about 250 feet of massive, chocolate-colored, cliff-forming, somewhat quartzitic sandstones overlain by 43 feet of thinly bedded, intercalated, brown sandstones and greenish shales, followed by 35 feet of white, cross-bedded sandstone. These beds, defined by Noble (1914) as the Tapeats sandstone, total 328 feet, although the average for the region is considerably less. In fact, as shown by Noble (1914) and Sharp (1940), these basal sandstones are in places absent because of nondeposition in the areas of Ep-Algonkian monadnocks, a few of which rise 800 feet above the peneplain surface.

This sandstone is the lithogenetic equivalent of the Prospect Mountain quartzite near Pierce Ferry at the western terminus of the Grand Canyon (Schenk and Wheeler, 1941). Gilbert (1875) noted Tonto sandstone in western Grand Canyon and the Grand Wash Cliffs region, and the Tapeats has been described by R. B. Wheeler and Kerr (1936) and by McKee (1939; 1940). Stoyanow (1936) reported it at Music Mountain near the southern extremity of Grand Wash Cliffs, 40 miles south of Pierce Ferry. Furthermore, this formation has been traced far into the Basin and Range region. Longwell (1928) questionably noted the Tapeats near the Key West mine in the Virgin Mountains of southeastern Nevada about 35 miles north of Pierce Ferry; and Hewett (1931) described an occurrence in Nevada near the Goodsprings quadrangle, about 80 miles southwest.

Thus the continuity of these basal sandstones or quartzites of the Granite Gorge Cambrian with those of southern Nevada has been well established. The logical course, therefore, is to name this widespread formation on the basis of priority of definition. In the interest of uniformity and consequent simplification of stratigraphic nomenclature, the name Prospect Mountain (Hague, 1883) is substituted for the subsequently proposed term Tapeats.

The Prospect Mountain formation of the Granite Gorge area is appreciably younger than in the region to the west and north. Walcott (1916) has described *Dolichometopus tontoensis* = *Anoria tontoensis*, together with several less diagnostic species, from the "Tapeats sandstone; about 300 feet (91.4 m.) above its base, at the head of Nunkoweap [Nankoweap] Valley [25 miles east of Bass Canyon] Grand Canyon. . . ." Noble (1922) showed this locality to be very near the top of the formation, since Walcott measured its thickness as 300 feet. In any event, this occurrence of *Anoria* indicates an early Medial Cambrian age for at least the uppermost beds of the Prospect Mountain formation at Nankoweap Valley. The limited thickness of Prospect Mountain sandstone in this region consists mostly, if not entirely, of shallow-water, littoral sediments and as such was deposited during a relatively short interval. Since an appreciable time-stratigraphic interval (including the *Albertella* and *Kochaspis liliana* biozones) intervenes between the *Anoria* zone and the top of the Lower Cambrian, the Prospect Mountain formation, in at least the eastern part

of the Granite Gorge area, should belong entirely to the Middle Cambrian. This view, based upon former, less detailed knowledge of Cambrian faunal zones, is shared by Walcott (1894, p. 518) and Noble (1922, p. 39).

BRIGHT ANGEL SHALE

Noble (1914) applied the name Bright Angel to the predominantly argillaceous rocks above the Prospect Mountain formation and below the Muav limestone in the Granite Gorge region and later gave a detailed description for Bass Canyon, about 16 miles northwest of Bright Angel Canyon, the type section (Noble, 1922). The lower member (B) at Bass Trail, as subdivided by Noble, consists of 333 feet of thinly bedded, greenish and buff, micaceous shale and sandstone, with two beds of "snuff-brown" dolomite in the middle portion forming two conspicuous cliffs. Glauconite is characteristic of many strata. The upper (A) member is 58 feet thick and is dominantly thinly bedded, greenish and buff shale and sandstone, with some beds of impure, mottled limestone and brown dolomite at the base.

Noble regards the "snuff-colored" carbonate rocks near the middle of member B as impure (arenaceous and ferruginous) dolomites. These beds appear to be identical with the "rust-colored" dolomites described by Schenk and Wheeler (1942) as the top and bottom members of the Lyndon formation in western Grand Canyon. That they are not the same, however, is assured by McKee (1938) who states that "the so-called 'snuff dolomites' . . . . of the Bright Angel shale are at different horizons at different localities and each is of relatively limited distribution. They appear to represent lateral transition stages . . . . between massive limestones and green shales." The dolomites immediately overlie the *Albertella* beds in western Grand Canyon, whereas they occupy a higher time-stratigraphic position in the Middle Cambrian (above *Alokistocare* and *Anoria*) in the Granite Gorge region.

Therefore, since the Lyndon formation does not continue eastward from western Grand Canyon to the Granite Gorge region as a cartographic unit, the underlying and overlying Pioche and Chisholm shales in the latter area merge into the Bright Angel shale. Thus beyond the eastern limit of recognition of the Lyndon in the Grand Canyon the Bright Angel must be recognized as a valid unit, corresponding to the combined Pioche, Lyndon, and Chisholm formations to the west.

Throughout the Granite Gorge region the Bright Angel shale appears to belong to the lower Middle Cambrian series. The following trilobites are among the faunas from various localities in the area listed by Walcott (1916), Noble (1922), and R. B. Wheeler and Kerr (1936): *Alokistocare althea* Walcott, *Anoria tontoensis* (Walcott), *Glossopleura mckeei* Resser, and *Kootenia* sp.

MUAV LIMESTONE

Above the thinly bedded, greenish and buff shale of the topmost Bright Angel at Bass Canyon Noble (1914; and 1922) described 473 feet of calcareous rocks with considerable intercalated shale and sandstone, designating it the Muav limestone. These strata, overlain unconformably by the buff and purplish mottled, sandy, magnesian limestones of the Devonian Temple Butte formation, are divided from top to bottom into the following subdivisions (Noble, 1922): A, buff, massive dolomite, 63 feet; B, buff, calcareous sandstone, thinly bedded at the base, 72 feet; C, thinly bedded,

mottled limestone, "intraformational" conglomerate, calcareous sandstone, and platy micaceous sandstone or shale, 241 feet; and D, gray and buff, thinly bedded, mottled limestone with shale partings in basal 10 feet, 97 feet.

As stated, strata lithogenetically equivalent to portions of the Muav limestone lie both above and below the Mead limestone in the western Grand Canyon. Since the Mead is unconformable to both the overlying limestone and underlying Peasley formation, and since it was completely eroded a few miles east of Grand Wash Cliffs, the two unconformities should merge eastward into one erosional break. Thus, beyond the eastern limit of the Mead formation, the name Peasley should be applied to the rocks below the unconformity.

Whether this Medial Cambrian hiatus is represented in the Granite Gorge region is not known. If it is, and if its presence can be discovered, the Muav limestone, as defined, would include two sequences separated by an unconformity and would require revision. Noble (1914; 1922) and Schuchert (1918) have described the abundant "intraformational" conglomerates in Noble's subdivision C of the Muav. The question arises as to whether these conglomerates are actually interformational, in part at least, and represent either the post-Mead or both the pre- and post-Mead hiatuses in the Granite Gorge region. Until this question is answered, the original designation of the Muav formation cannot be discredited.

The age of the Muav limestone has been discussed at some length (Walcttt, 1912, p. 214; Noble, 1914; 1922; Schuchert, 1918). Whether it is Middle or Upper Cambrian, on the basis of the rather meager faunas, appears to have been debatable. However, the discovery of specimens of *Asaphiscus* and *Solenopleurella* in the Muav limestone proves that at least part of the formation is Middle Cambrian.

CAVE VALLEY, NEVADA

GENERAL STATEMENT

The foregoing discussion presents a description of all sequences which include type sections of the formations involved in correlations. The successions at Cave Valley and Delamar, and in the Mormon and Virgin mountains of Nevada utilizes these previously described formations and considers their stratigraphic and faunal relationships in the intervening areas.

The earliest mention of Cambrian rocks in the vicinity of the Cave Valley (Patterson or Geyser) district was by Spurr (1903, p. 40) who cites Howell's (1875) description of quartzite and limestone. Howell correctly correlated the strata with similar ones in the Snake and Highland ranges but erred in assigning them all to the Carboniferous. Spurr mentions the Cambrian age of the rocks in the Snake Range and states that F. B. Weeks collected Cambrian fossils from the limestones near Patterson. Hill (1916) prepared structure sections in the Schell Creek Range in the vicinity of Patterson Pass which show the regional eastward dip and the presence of "100 feet" of argillaceous beds between the quartzite and limestone.

Schrader (1931a) briefly discusses the stratigraphy in connection with the ore deposits of the Cave Group of mining claims located on a low, isolated, westerly trending spur on the western flank of the Schell Creek Range, about 5 miles northwest of Patterson Pass. This spur lies, in general, along the line between sections 9 and 16, T. 9 N., R. 64 E., in northernmost Lincoln County. He prepared a longitudinal

cross section of the spur on almost the same line as the one presented here (Fig. 3). The Cave Valley cave is in limestones exposed on the western third of the spur. Schrader recognized quartzite, schist, shale, and limestone and stated that fossils from the limestone above the quartzite had been determined by Edwin Kirk of the United States Geological Survey as Cambrian algae.

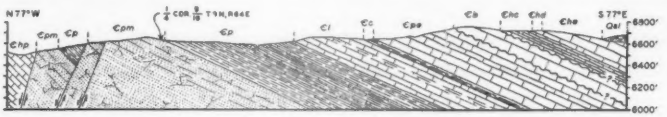


FIGURE 3.—*Cross section through Cambrian at Cave Valley, Nevada*

Cpm = Prospect Mountain quartzite; Cp = Pioche shale; Cl = Lyndon limestone; Cc = Chisholm shale; Cpe = Peasley limestone; Cb = Burrows limestone; Chc, Chd, Che = Highland Peak limestone units C, D, and E; Chp = undifferentiated Highland Peak.

Time did not permit the writer to search for additional fossils. The rocks are correlated confidently on lithology and orderly succession of nine lithogenetic units, all of which are recognized in the Pioche district, and two of which may be identified at Eureka.

Howell (1875), Spurr (1903), and Hill (1916) placed the quartzite at the base of the Cambrian succession exposed in the Schell Creek Range. Although Schrader (1931a) stated that the apparent great thickness of the rocks may involve some duplication by faulting, he showed the easterly dipping quartzite in normal sedimentary contact upon 1500 feet or more of limestone. A west-dipping normal fault with several hundred feet of throw forms the contact between the limestones and the quartzite. (*See* Figure 3.) In fact, the western part of the ridge was not sectioned because numerous repetitions by faulting render it worthless for stratigraphic purposes. A few hundred feet east of the quartzite-limestone fault are two others of smaller displacement, the second repeating the normal contact between the quartzite and overlying Pioche shale. Eastward from this zone of faulting lies a normal Lower and Middle Cambrian sequence 1940 feet thick, unbroken along the line of section by faults of significant displacement, although a prominent east-west fault zone closely approaches on the south side of the spur.

The following section briefly outlines the lithology and thickness of the Cambrian formations and subdivisions exposed on this spur.

CAMBRIAN SECTION AT CAVE VALLEY

	Feet
MIDDLE CAMBRIAN	
HIGHLAND PEAK LIMESTONE	
Unit E	
Limestone: mostly light and medium-gray, dense to medium-grained, thinly to thickly bedded, somewhat dolomitic. This unit, wherever recognized, is characterized by its heterogeneity of calcareous types. (Top covered)	150
Unit D	
Limestone: light-gray to white, massive	40
Unit C	
Limestone: dark-gray (almost black) carbonaceous, fine-to medium-grained, thinly and distinctly bedded (6 inches to 2 feet)	120
Total thickness of exposed Highland Peak limestone	310
Unconformity (?)	

	Feet
BURROWS LIMESTONE	
Limestone: medium-gray, fine-grained to dense, thick bedded to massive	25
Limestone: light-gray (almost white), dense	135
Limestone: thinly interbedded light- and dark-gray, fine-grained (banded effect)	30
Total thickness of Burrows limestone	190
Unconformity (?)	
PEASLEY LIMESTONE	
Limestone: medium- to dark-gray (carbonaceous), medium-grained, thickly bedded to massive	245
Limestone: medium- to dark-gray (carbonaceous) medium-grained, thinly to thickly bedded	85
Limestone: medium- to dark-gray, medium-grained, thinly and distinctly bedded	30
Total thickness of Peasley limestone	360
CHISHOLM SHALE	
Shale and limestone: brownish to buff, fine-grained, micaceous shale, interbedded with numerous, thin layers of argillaceous limestone	45
Total thickness of Chisholm shale	45
LYNDON LIMESTONE	
Limestone: medium-gray, fine- to medium-grained, medium-bedded	90
Limestone: mostly dark-gray (carbonaceous), medium-grained, thin- to medium-bedded, with shale partings	35
Limestone: medium-gray, fine- to medium-grained, medium-, thick-, and massive-bedded	155
Total thickness of Lyndon limestone	280
LOWER CAMBRIAN	
PIOCHE SHALE	
Shale: Brownish-buff, fine-grained, micaceous (sericitic)	60
Limestone and shale: micaceous, shale interbedded with medium-gray limestone	7
Shale: Brownish-buff, micaceous shale	30
Limestone and shale: 60 per cent medium-gray, thickly bedded limestone interbedded with 40 per cent micaceous shale	65
Shale: Brownish-buff, fine-graned, micaccous	30
Limestone: medium-gray, thickly bedded to massive, algal	25
Shale and limestone: Brownish-buff, micaceous shale; 1-foot limestone bed 32 feet above base, and 3-foot limestone bed 49 feet above base	65
Limestone: Medium-gray, thickly bedded to massive	18
Shale: Reddish-brown to buff, fine- to medium-grained, micaceous (sericitic), more arenaceous and quartzitic near the base	205
Total thickness of Pioche shale	505
PROSPECT MOUNTAIN QUARTZITE	
Quartzite: white to pale-pink and buff, massively bedded	90
Quartzite and shale: Reddish-brown, thin- to medium-bedded quartzite with some intercalations of micaceous, quartzitic shale	160
Base faulted out.	
Total thickness of exposed Prospect Mountain quartzite	250
Total thickness of exposed Cambrian at Cave Valley	1940

The exposed portion of the Prospect Mountain quartzite at Cave Valley is only 250 feet thick, but the thickness in the Patterson district is appreciably greater, as evidenced by exposures in the main mass of the Schell Creek Range immediately eastward. The writer believes that no less than 1000 feet of quartzitic strata is exposed on the slopes of Patterson Mountain, and in Swartz Canyon Hill (1916) mentions "400 feet of light-colored quartzite, which in turn overlies a great thickness of dark reddish-brown quartzite." Additional evidence that the quartzite in the Patterson area even exceeds 1000 feet is indicated by its thickness in three widely divergent directions: Eureka, northwestward 1660 feet plus; Snake Range, northeastward, 2500 feet (Spurr, 1903); and Pioche, southward, 2000 feet plus. Cursory

examination suggests that strata above the Middle Cambrian Unit E of the Highland Peak formation will be found in the main mass of the Schell Creek Range.

AGE OF CAVE VALLEY CAMBRIAN

In the preceding section, the Pioche shale and the exposed portion of the underlying quartzite are listed as Lower Cambrian, the overlying formations as Middle

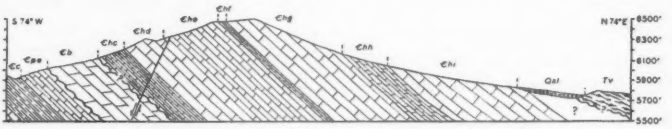


FIGURE 4.—*Cross section through upper part of Cambrian sequence at Delamar, Nevada*
Cc = Chisholm shale; Cpe = Peasley limestone; Cb = Burrows limestone; Chc to Chi = Highland Peak limestone Tv = Tertiary (?) volcanica; Qal = alluvium.

Cambrian. The Lyndon limestone is lower Middle Cambrian from its type locality in the Pioche district southward 150 miles to western Grand Canyon. Therefore, it should be Middle Cambrian only 55 miles north of its type locality, especially since the upper 370 feet of the 970 feet of underlying Pioche shale in the Pioche district is Middle Cambrian, the lower 600 feet being Lower Cambrian. At Eureka the Pioche shale is reduced to 200 feet with *Olenellus* in the upper half. Thus the significant change of facies between the Pioche and Eureka districts involves the progressive lateral gradation of the uppermost shale into limestone. The 505 feet of Pioche shale at Cave Valley is 465 feet less than the 970 feet at the type locality, and since this 465 feet only slightly exceeds the 370-foot Middle Cambrian part at Pioche, the Lower-Middle Cambrian boundary at Cave Valley may be very near the Pioche shale-Lyndon limestone contact.

At Cave Valley, as elsewhere in the region, part of the unexposed Prospect Mountain quartzite may be pre-Cambrian.

DELAMAR DISTRICT, NEVADA

GENERAL STATEMENT

The Delamar or Ferguson district is located in an unsurveyed area on the west slope of the Meadow Valley Range, in central Lincoln County, Nevada, about 17 miles (in direct line) southwest of Caliente.

Emmons (1902) first mentioned the sequence of quartzite, shale, and limestone in this district but did not date it. Spurr (1903, p. 149) stated that Emmons believed the strata are Cambrian. Callaghan (1937) presented detailed descriptions of the Pioche shale, Lyndon limestone, and Chisholm shale and briefly described the Prospect Mountain quartzite and strata which he questionably assigned to the Highland Peak limestone. He also listed faunas from the Pioche and Chisholm shales.

Callaghan's section from the Prospect Mountain quartzite to the base of the Highland Peak limestone was measured "on the mountain front about two miles north of Monkey Wrench Wash," or about 4 miles north of the old mining camp of Delamar. The accompanying cross section (Fig. 4) of the exposed succession of the Peas-

ley, Burrows, and Highland Peak limestones was taken about 3 miles southeast of Delamar, across the 6450-foot saddle on the prominent limestone ridge at the head of Big Lime Wash, near the south boundary of Callaghan's (1937, Fig. 2) map area. The section trends eastward from the Chisholm shale through 2460 feet of exposed Highland Peak limestone to the unconformable contact with the overlying Tertiary (?) volcanics. Thus in the following section of the Delamar district Cambrian the Pioche-Lyndon-Chisholm portion and the Peasley-Burrows-Highland Peak portion are measured at localities about 7 miles apart. Exposed thickness of the Prospect Mountain quartzite is estimated from various exposures in the district as being over 1000 feet; the base was not seen.

CAMBRIAN SECTION OF THE DELAMAR DISTRICT

	Feet
TERTIARY(?)	
Effusives and pyroclastics: andesitic, dacitic, and latitic flows with associated tuffs and breccias, overlain by rhyolite flows (Callaghan, 1937)	2000+ (?)
Unconformity	
MIDDLE CAMBRIAN	
HIGHLAND PEAK LIMESTONE	
Unit I	
Limestone: Mostly dark gray (carbonaceous) fine-, medium-, to coarse-grained, thickly and distinctly bedded to massive	600+ (?)
Unit H	
Dolomite and limestone: mostly light-gray to white, dense, laminated, "primary" dolomite with blocky fracture, interbedded with some fine-grained, medium-gray limestone	225
Unit G	
Limestone: mostly dark-gray, medium-grained, thickly and distinctly bedded, somewhat mottled, carbonaceous	550
Unit F	
Sandstone: mostly buff-colored, fine-grained thinly bedded to laminated, platy, dolomitic	55
Unit E	
Limestone and dolomite: light-, medium-, and dark-gray, dense to coarse-grained, thinly to thickly bedded (heterogeneous). Upper portion somewhat dolomitized	465
Unit D	
Limestone: light-gray to almost white, dense, massive. This unit may be thickened locally by faulting and, as measured, may include some of the lowermost beds of Unit E	325 (?)
Unit C	
Limestone: dark-gray (carbonaceous), thin-, medium-, and distinctly bedded	240
Total thickness of exposed Highland Peak limestone	2460
Unconformity (?)	
BURROWS LIMESTONE	
Limestone: mostly dense, massive, light-gray to white (partially dolomitized)	420
Total thickness of Burrows limestone	420
Unconformity	
PEASLEY LIMESTONE	
Limestone: mostly dark-gray (carbonaceous), medium-grained, thickly bedded to massive. Weathered, rough surfaces show irregular banding or mottling in zones of intercalated impurities	235
Total thickness of Peasley limestone	235
CHISHOLM SHALE[4]	
Shale and thin limestone beds	127
Limestone	6

[4] Except for the position of the Lower-Middle Cambrian boundary the following section of the Chisholm, Lyndon, and Pioche formations is taken from Callaghan (1937, p.17–18) and was measured at the west base of the Meadow Valley Range, about 4 miles north of Delamar.

	Feet
Shale and thin limestone beds	38
Limestone	6
Shale and thin limestone beds	123
Total thickness of Chisholm shale	300
LYNDON LIMESTONE	
Limestone: massive gray to black	102
Total thickness of Lyndon limestone	102
MIDDLE AND LOWER CAMBRIAN	
PIOCHE SHALE	
Shale: brownish sandy; uppermost 2 feet a shaly quartzite	25
Limestone: massive	12
Limestone: brown shaly	2
Limestone: massive	17
Shale	30
Shale: calcareous shale	4
Limestone: thin-bedded with red bands and lenses	7
Shale: greenish shale	3
Limestone: thin-bedded brown and black, with *Girvanella* at top	6
Limestone: black, with *Girvanella* abundant	12
Shale	9
Limestone: thin-bedded	11
Shale: brown sandy	2
Shale with thin limestone beds	68
Limestone	2
Shale with thin limestone beds	93
Shale and limestone: brownish shale with thin limestone beds	75
Limestone: thin-bedded	8
Shale: brownish calcareous and sandy	77
Limestone: thin-bedded	10
Shale: greenish shale with some calcareous beds	157
Limestone: numerous trilobite fragments in shale immediately above	6
Shale	24
Limestone	5
Shale	38
Covered: possible faults and may include some Prospect Mountain quartzite	185
Total thickness of Pioche shale	888
LOWER CAMBRIAN	
PROSPECT MOUNTAIN QUARTZITE	
Quartzite and shale: light-gray (nearly white) and pink to reddish-brown, thin-, medium-, and thick-bedded quartzite with intercalated shales and some conglomerate; cross-bedding frequent. (Estimated thickness of exposed Prospect Mountain quartzite in Delamar district)	1000+
Total estimated thickness of exposed Cambrian of the Delamar district	5405+

In this section, the thicknesses of Highland Peak limestone units D and I are questioned. Unit I is partly covered near the east end of the section (Fig. 4) and may be somewhat faulted. The thickness of Unit D appears to be excessive when compared with the 30 to 40 feet in the Pioche and Cave Valley districts. A part of this apparently excessive thickness may be due to faulting other than that shown in Figure 4, although the writer has noted two exposures in the Pioche district wherein the lowermost 50 or 60 feet of Unit E strata closely resembles Unit D because of local phase conditions. Additional work on this part of the Highland Peak formation in the Delamar district may prove that some of the beds designated as Unit D actually belong to Unit E.

AGE OF DELAMAR CAMBRIAN

In the absence of faunal evidence the exposed units of the Highland Peak limestone at Delamar (C to I) are assigned to the Middle Cambrian as they are at Pioche on

partial faunal evidence. However, since the Middle-Upper Cambrian boundary has not been located precisely in any eastern Nevada sequence, it may be below the highest exposed beds in the Delamar district. If the lower Highland Peak strata are contemporaneous with their Pioche equivalents, they may be upper Middle Cambrian.

The Peasley and Burrows formations at Delamar may be assigned safely on the same basis to the Middle Cambrian, especially since the Peasley immediately overlies the Chisholm shale which carries lower Middle Cambrian fossils. Callaghan (1937) lists *Glossopleura parabola* (Hall and Whitfield), *Iphidella panula* (White), *Hyolithes* sp., and *Westonia* (?) sp. from beds 80 feet below the top of the Chisholm shale, a fauna clearly indicating an early Medial Cambrian age in the Delamar area. The Lyndon limestone is early Medial Cambrian both to the north (Pioche) and south (Mormon Range and western Grand Canyon).

The Pioche shale at Delamar is assigned to both the Lower and Middle Cambrian series. From "probably within 300 feet of the base of the formation" Callaghan (1937) reports *Olenellus gilberti* Walcott, *Peachella iddingsi* (Walcott), and *Calavia* (?) *nevadensis* Walcott. Thus the lower beds belong in part at least to the Lower Cambrian *Olenellus* biozone. However, since the Pioche shale encloses both Lower and Middle Cambrian faunas in western Grand Canyon, Mormon Range, and the Pioche district, the upper portion of the formation at Delamar must be Middle Cambrian. The Lower-Middle Cambrian boundary is questionably and arbitrarily plotted by interpolation on the accompanying columnar section (Pl. 1) 350 feet below the top or 538 feet above the base of the measured section of the Pioche.

The topmost beds of the Prospect Mountain quartzite, in view of their close proximity to the *Olenellus* fauna of the overlying Pioche shale, are assigned to the Lower Cambrian. The entire exposed thickness at Delamar may belong to that series, but these arenaceous deposits may be in part pre-Cambrian.

MORMON RANGE, NEVADA

GENERAL CONSIDERATIONS

Longwell (1926) briefly mentioned Cambrian rocks in the Mormon Range.

Both Archean metamorphics and marine Cambrian have been found approximately in Sec. 22, T. 12 S., R. 69 E., in southeastern Clark County, Nevada, about 12 miles west of the Arizona boundary. Unfortunately, a part of the Cambrian sequence is faulted out so that the section is inadequate for stratigraphic purposes.

About 4 miles northwest in NE. $\frac{1}{4}$ Sec. 14 and NW. $\frac{1}{4}$ Sec. 13, T. 12 S., R. 68 E., crossing the Glendale-Carp-Caliente road immediately south of the low summit, in Lincoln County about 4 miles north of the Clark County line, an excellent section from the Prospect Mountain quartzite to the Peasley limestone is exposed. The unbroken portion of the Cambrian, dipping 23° to 50° E., is in fault contact on the west with Carboniferous (?) secondary dolomite and on the east with Middle Cambrian (?) or younger rocks.

The following stratigraphic section is based upon this exposure, a cross section of which is shown in Figure 5. Dr. Charles Deiss identified the fossils.

CAMBRIAN SECTION IN THE MORMON RANGE

	Feet
MIDDLE CAMBRIAN	
PEASLEY LIMESTONE	
Dolomite: medium-gray, coarse-grained, brecciated, massive, secondary (dolomitized and brecciated near fault)	360
Limestone and dolomite: medium-gray, medium-grained, massive, cliff-forming limestone with dolomite mottling and rough weathered surface	50
Total thickness of exposed Peasley limestone	410

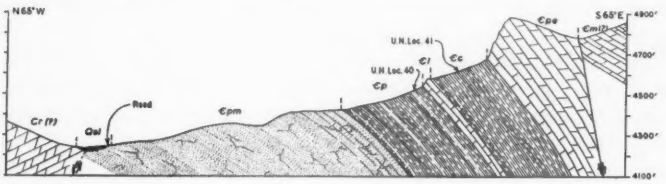


FIGURE 5.—*Cross section through Cambrian in Mormon Range, Nevada*

Cpm = Prospect Mountain quartzite; Cp = Pioche shale; Cl = Lyndon limestone; Cc = Chisholm shale; Cpe = Peasley limestone; Cm(?) = undifferentiated Middle (?) Cambrian; Cr(?) = Rogers Spring (?) limestone (Carboniferous).

CHISHOLM SHALE	
Shale: dull-green, thinly laminated	29
Limestone: medium-gray, algal	1
Shale: dull-green, thinly laminated, with calcareous bed of "trilobite hash" (stratigraphically unallocated)	115
Limestone: medium-gray, thin-bedded (½ to 1 inch), irregularly bedded, with buff shale partings up to ½ inch thick. Fossils (U. N. locality 41): *Glossopleura alta* Deiss, *G.* cf. *fordensis* Deiss, and *G.* cf. *nitida* Resser	6
Shale and sandstone: greenish and red-brown, thinly laminated shale intercalated with thinly bedded (almost laminated), micaceous sandstone	124
Total thickness of Chisholm shale	275
LYNDON LIMESTONE	
Limestone: medium-gray, medium-grained, thinly but indistinctly bedded, rough-surfaced, mottled, with yellow-buff, irregular shale partings; numerous calcite stringers	50
Total thickness of Lyndon limestone	50
MIDDLE AND LOWER CAMBRIAN	
PIOCHE SHALE	
Shale: tan to green-tan, micaceous, irregularly laminated, with several intercalated thin beds of quartzite and limestone. Fossils (U. N. locality 40, 40 feet below base of Lyndon): *Albertella* sp. and *Ptarmigania* sp.	80
Shale: green, thinly laminated (papery), with few 4- to 6-inch quartzite beds; 18-inch, rusty-brown, sandy dolomite at top; 18-inch bed of gray, coarse-grained, cross-bedded quartzite at base	90
Shale: green, micaceous, arenaceous, irregularly laminated	7
Quartzite: gray	2
Dolomite: rusty-brown, sandy	5
Shale: green-tan (olive-green unweathered), micaceous, thinly laminated (papery), with numerous trilobite tracks; 1-foot bed rusty-brown dolomite at base and few thin sandstone layers in upper portion	86
Shale and quartzite: greenish-gray, olive-drab, tan and brown, micaceous shale with some thin quartzitic layers	70
Total thickness of Pioche shale	340
LOWER CAMBRIAN	
PROSPECT MOUNTAIN QUARTZITE	
Quartzite and shale: interbedded thin quartzite beds and olive-drab and brown, micaceous and arenaceous shale	90
Quartzite: mostly light-gray to white, medium- to coarse-grained, thick-bedded to massive	20

	Feet
Quartzite: mostly red-brown, medium- to coarse-grained, thin-, thick-, to massive-bedded; some arkosic; some cross-bedded and ripple-marked; minor amount white to light-gray and pink	690
Base covered.	
Total thickness of exposed Prospect Mountain quartzite	800
Total thickness of exposed Cambrian in Mormon Range	1875

AGE OF MORMON RANGE CAMBRIAN

Diagnostic fossils have been found in the Mormon Range succession only in the Pioche and Chisholm shales. An *Albertella* fauna is present 40 feet below the top of the Pioche shale, and the *Glossopleura* biozone is represented near the middle of the Chisholm shale. Thus these formations, except for differences in thickness, have essentially the same faunal and stratigraphic relationships as at Delamar and Pioche to the north and western Grand Canyon to the south. Therefore, the upper part of the Pioche shale and the Lyndon, Chisholm, and Peasley formations are early Medial Cambrian and embrace the zones from *Albertella* to *Glossopleura*.

Identifiable fossils have not been found in the lower part of the Pioche shale. Nevertheless, the *Olenellus* fauna in these beds at both Delamar and western Grand Canyon suggest that the lower portion of the Pioche shale in this region is also Lower Cambrian, although Longwell (1926, p. 556) stated that Lower Cambrian clastics are not present in the Mormon Mountains. The position of the Lower-Middle Cambrian boundary is unknown. The accompanying columnar section (Pl. 1) illustrates that it has been placed by interpolation 200 feet above the base of the formation.

The exact thickness of the Prospect Mountain quartzite in the Mormon Range sequence is not known because alluvial cover and faulting limit the exposed strata. At the locality in Clark County where the quartzite adjoins Archean metamorphics, its thickness is less than 500 feet. This is in accord with the 295-foot Tapeats(?) thickness reported by Longwell (1929) from near Whitney Ranch in the Virgin Mountains, about 30 miles southeast, and with 440 feet measured near the Key West mine about 10 miles northwest of Longwell's Virgin Range section. By interpolation, the thickness of the quartzite of the measured Mormon Range sequence should little exceed the exposed 800 feet. If the thickness is about 1000 feet, the entire Prospect Mountain quartzite in this vicinity probably lies within the Lower Cambrian.

Because the pre-Cambrian metamorphics are exposed in sedimentary contact with the quartzite only 4 miles away, they are shown in the columnar section (Pl. 1).

WHITNEY RANCH, VIRGIN MOUNTAINS, NEVADA

GENERAL STATEMENT

The only adequate published description of the Cambrian succession in the Virgin Mountains of southeasternmost Nevada is that of Longwell (1928). He briefly mentioned the quartzite, shale, and limestone exposed in the vicinity of the Key West mine on the northwest slope of the range about 8 miles west of the Arizona boundary at Lat. 36° 36′ N., called attention to the similarity of the detrital formations to the Tapeats-Bright Angel sequence of the Grand Canyon region, and noted

that some of the overlying limestones may correspond to the Muav limestone of the Grand Canyon and the Hamburg limestone of the Eureka district, Nevada.

Ten miles southeastward, immediately south of Whitney Ranch and immediately west of the Nevada-Utah boundary, on the southeastern flank of the mountains, Longwell (1928) presented the following section of the strata lying beneath 2585 feet of undetermined Paleozoic beds[9] (author's revision in brackets):

	Feet
CAMBRIAN (?) [MIDDLE CAMBRIAN:]	
MUAV LIMESTONE (?)—[PEASLEY LIMESTONE][10]	
Dark-gray compact limestone; has massive appearance in cliffs but in many places weathers into thin layers; has light-gray and brown mottling; very uniform in character except for a few thin gritty layers of light-buff color	775
BRIGHT ANGEL SHALE (?)—[CHISHOLM SHALE]	
Paper shale, micaceous, green and maroon; near base are thin limestone layers with trilobites	65
Thin layers of limestone with trilobites	6
[LYNDON LIMESTONE]	
Compact dark-gray limestone forming cliff; has many alga-like patterns near base; brown mottling near top; appears massive, but has thin lamination	45
[MIDDLE AND LOWER CAMBRIAN:]	
[PIOCHE SHALE]	
Thin micaceous shales, largely sandy, with recurring sandstone layers, predominantly olive-green with some brownish beds; contains abundant casts of worm trails	195
[LOWER CAMBRIAN:]	
TAPEATS SANDSTONE (?)—[PROSPECT MOUNTAIN QUARTZITE]	
Thin-bedded sandstone, brownish, gray, and olive-drab, with recurring layers of cross-bedded gray quartzitic sandstone (like that below); forms slope with broken outcrop; many layers knobby with markings like worm trails	95
Sandstone and quartzite, cross-bedded in layers ranging from a few inches to 5 feet thick; near base strongly arkosic and reddish brown; grows more quartzose and gray upward; generally of medium and fine grain, with conglomerate lenses, not noticeably coarser at base	200
Unconformity; granite below shows disintegration to shallow depth.	
PRE-CAMBRIAN: Mica gneiss, mica schist, and coarse, lustrous amphibolite; gray gneissoid granite intrudes the schistose rocks and in turn is cut by dikes of coarse-grained pink granite; granite also cut by dike of fine-grained dolerite, which ends at the unconformity.	

AGE OF WHITNEY RANCH CAMBRIAN

Longwell reported unidentified trilobites in thin limestones near the base of the Chisholm shale portion of his "Bright Angel shale (?)". Nevertheless, the lithostratigraphic relationships, except for moderate differences in thickness and other minor lithologic variations resulting from slight lateral change of facies, are the same as those in the Mormon Range to the north and in western Grand Canyon to the south. Therefore, as in these adjacent areas, the Prospect Mountain quartzite is assigned to the Lower Cambrian, the Pioche shale to the Lower and Middle Cambrian, and the Lyndon, Chisholm, and Peasley formations to the lower Middle Cambrian.

Additional work is necessary to determine whether the Mead limestone of near-by western Grand Canyon is present in the Whitney Ranch sequence, and, if so, whether it constitutes a part of the limestones here assigned to the Peasley formation. Further investigation also may prove the presence of additional Cambrian strata above those assigned to the Peasley, as suggested by Longwell (1928, p. 24).

[9] This Whitney Ranch Cambrian sequence is now under study by Mr. John Shelton of Pomona College, California.

[10] This unit may include the Mead limestone (Schenk and Wheeler, 1942) of the western Grand Canyon area or the Burrows limestone (Wheeler, 1940) of the Pioche district if the Mead and Burrows are the same.

REGIONAL CORRELATIONS AND SUMMARY

GENERAL STATEMENT

Most of the lithogenetic units are widespread and remarkably uniform in lithology; sufficient data are at hand for a more comprehensive synthesis of the Cambrian relationships of the southwestern Cordilleran region. This simplification of formational nomenclature, extensively applicable as it may be roughly parallel to the geosynclinal axis, cannot be employed throughout the entire southern Cordilleran basin. Depositional facies relationships change appreciably as the margins of the trough are approached, thus necessitating different formation names. For example, the Bright Angel formation is applicable in the Granite Gorge region of the Grand Canyon, whereas it conflicts with its lithogenetic equivalent to the west and northwest which is more satisfactorily subdivided into the Pioche, Lyndon, and Chisholm formations. The writer believes that nomenclatural simplification results in a much better appreciation of the regional lithologic, faunal, and time-stratigraphic relationships (Pls. 1, 2).

The lithogenetic units also differ in age from place to place. In other words, formational contacts cross time boundaries, necessitating a discrimination of lithogenetic and time-stratigraphic units such as that proposed by Schenck and Muller (1941).

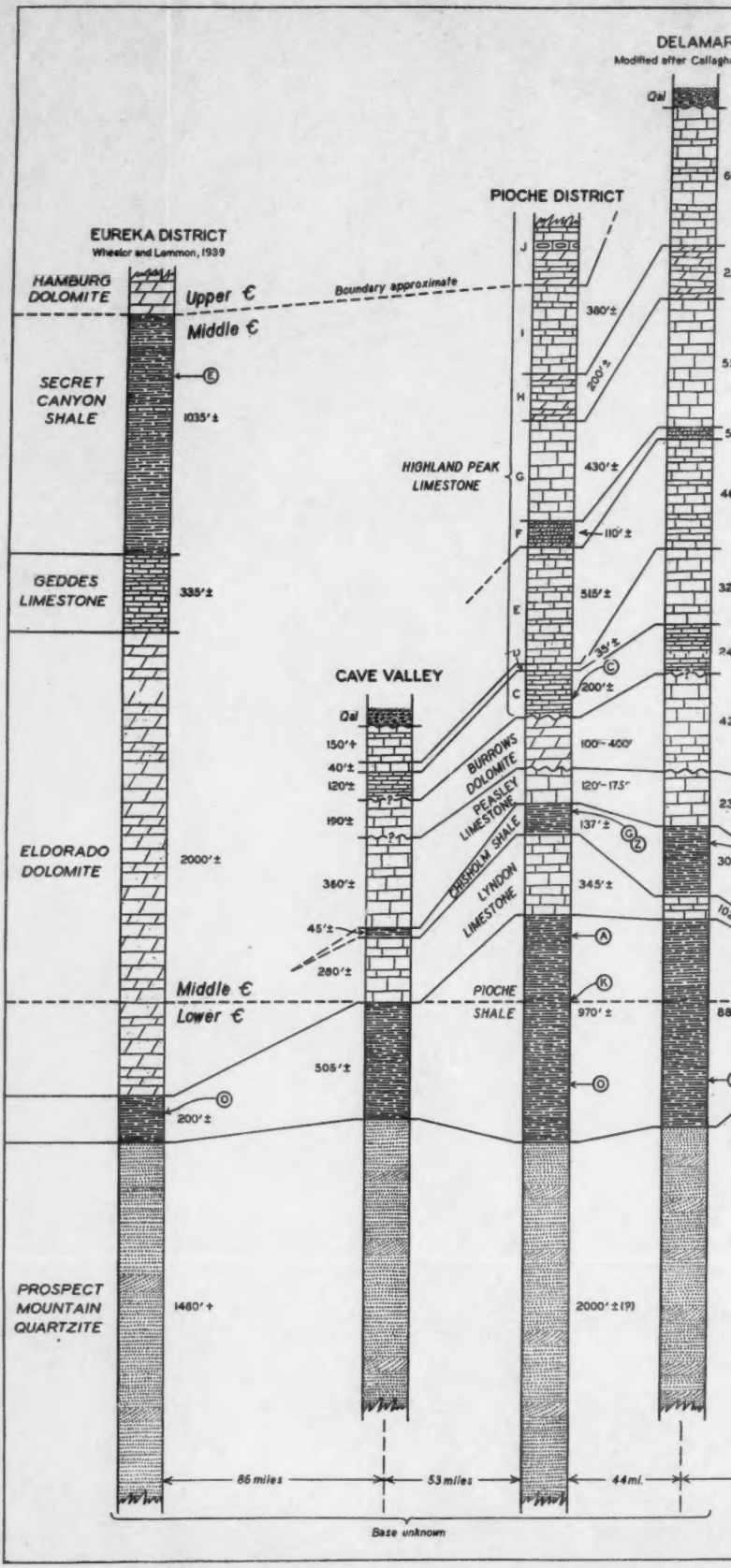
PROSPECT MOUNTAIN QUARTZITE

(Nevada, Arizona, Utah, and Idaho)

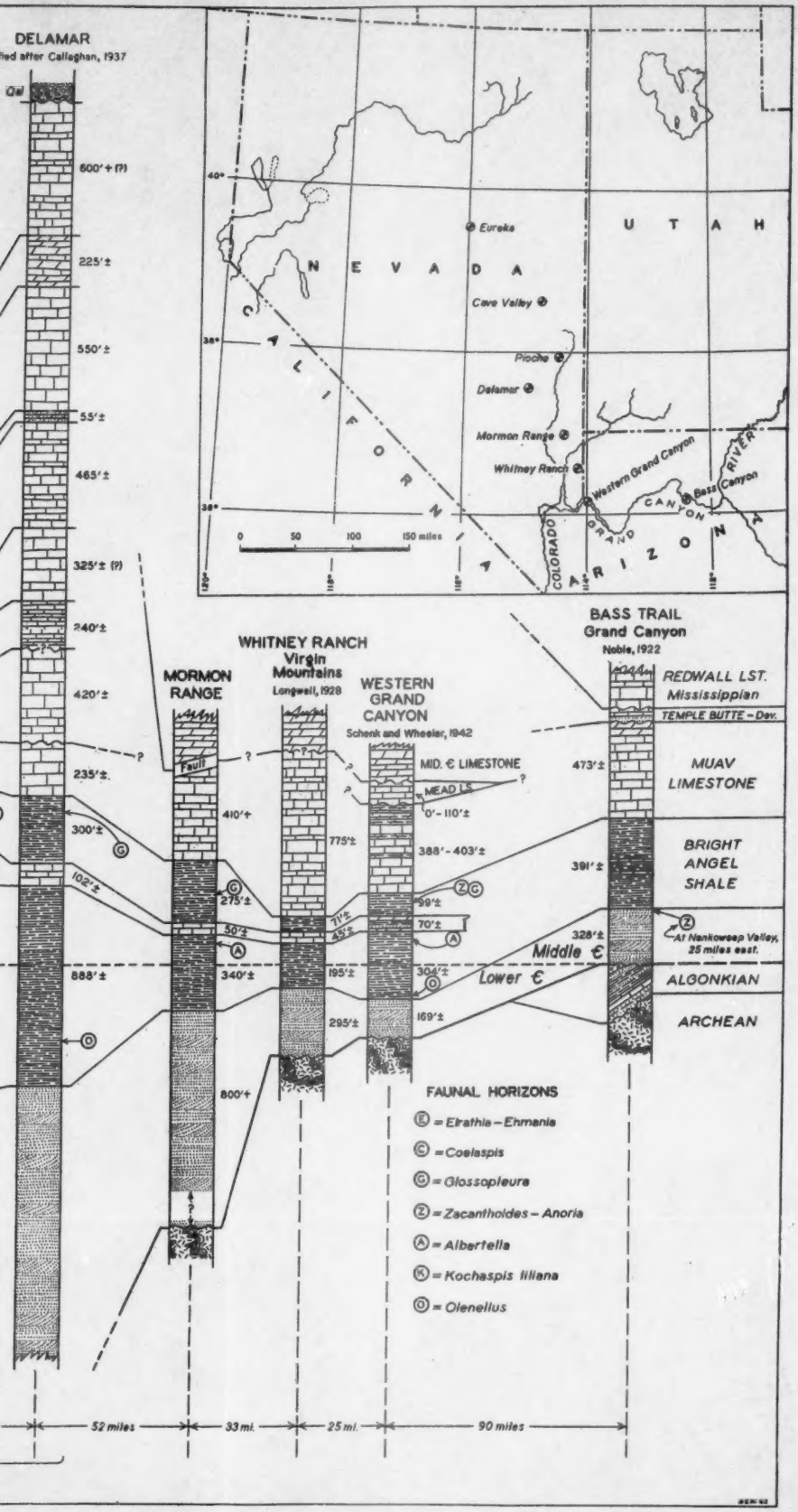
Apparently the most widespread southern Cordilleran Cambrian formation is the Prospect Mountain quartzite. These basal Paleozoic detrital sediments extend from northeastern Nevada southward into central Arizona and eastward throughout western Utah and southeastern Idaho.

At its type locality in the Eureka district, Nevada, the Prospect Mountain has an exposed thickness of 1460 feet though the base was not seen. The Eureka district long has been thought the approximate northern limit of earliest Cambrian sedimentation in the southern Cordilleran region. For example, Deiss (1941, p. 1107, Fig. 8) shows no early Waucobian sedimentation along the Fortieth Parallel. Sharp (1942), however, measured 1400 feet of Prospect Mountain quartzite in the southern Ruby Mountains, Nevada, immediately north of the Fortieth Parallel (base unexposed) and stated that the formation is widely distributed in the northern two-thirds of the range.

South of Eureka the Prospect Mountain formation extends for more than 450 miles to central Arizona, thinning to its ultimate southern shore line. The Prospect Mountain formation in the Pioche district is estimated to be more than 2000 feet thick, and 1000 feet or less in the Mormon Range. It measures 295 feet at Whitney Ranch in the Virgin Range, 169 feet in western Grand Canyon, "about 100 feet" at the southern end of the Juniper Mountains (Lee, 1908), 75 to 80 feet at Jerome (Ransome, 1916), and 110 feet where the road from Payson to Pine crosses East Verde River in northern Gila County. Stoyanow (1936) believes the last locality to be in the vicinity of the ultimate southern shore line of the Tonto sea, as evidenced by the absence of Cambrian strata over an appreciable area to the south ("Mazatzal



LOWER AND MIDDLE CAMBRIAN COLUMNAR SECTIO



R SECTIONS IN EASTERN NEVADA AND NORTHERN ARIZONA

land") and by the occurrence of well-rounded boulders of Mazatzal quartzite in the Tapeats near Natural Bridge, about 4 miles north of East Verde River.

Throughout eastern Nevada, the topmost strata are Lower Cambrian and immediately precede the *Olenellus* fauna. In southeasternmost Nevada (Virgin Range and Iceberg Canyon of the Colorado River) and in northwesternmost Arizona (western Grand Canyon and Grand Wash Cliffs) the formation rests upon pre-Cambrian eruptive and metamorphic rocks and is limited to a few hundred feet in thickness. In this region, the entire formation seems Lower Cambrian.

On the other hand, in westernmost Utah (Gold Hill and House Range) and in eastern Nevada (Snake Range, Pioche, Eureka) the exposed thicknesses suggest that several thousand feet of quartzite were deposited throughout the region. The writer doubts that several thousand feet of sediment could accumulate over such a wide area in earliest Cambrian prior to *Olenellus* time. Many geologists expect a well-defined and "profound" unconformity at the base of the Cambrian and in its absence do not think that local sedimentation may have begun in late pre-Cambrian time. For example, in the Nopah and Resting Springs mountains of southeastern California, more than 8500 feet of unfossiliferous strata below an *Olenellus* fauna are designated as Lower Cambrian by Hazzard (1938) because of a "marked angular unconformity" below and the possible absence of one within. The same "marked unconformity" is present in both southeastern California and in northern Arizona, but sedimentation following the erosion interval in the latter region began much later than in the former, disproving the validity of regional unconformities in establishing the age of overlying strata. If sedimentation did not begin until Medial Cambrian time in some of the areas of the Cordilleran basin, could it not have begun in late pre-Cambrian time in the regions of earliest inundation? This seems especially likely in areas of excessive thicknesses of "Lower Cambrian" strata. Failure to at least consider such possibilities and to date formations accordingly only contributes to the long-standing and widespread misapprehensions regarding the relationships between rocks and time and the role of diastrophism in stratigraphic geology.

The writer therefore classifies the Prospect Mountain quartzite in eastern Nevada and westernmost Utah as Lower Cambrian and Upper pre-Cambrian (?).

Eastward and southward from southeasternmost Nevada and western Grand Canyon in northwestern Arizona, in consequence of the gradual southeasterly advance of the Cambrian shore lines, the basal quartzite becomes progressively younger. In the Lake Mead region the formation is assigned to the Lower Cambrian (pre-*Olenellus*), whereas at Nankoweap Valley 120 miles eastward in the Granite Gorge region the entire sequence (Tapeats sandstone) appears to be early Medial Cambrian. At the latter locality the topmost beds of the Prospect Mountain carry the *Anoria* fauna which is not the earliest Medial Cambrian fauna.

A similar change in the age of the quartzite is inferred for the region south of western Grand Canyon. Stoyanow (1936) implies that Middle Cambrian trilobites have been found in the topmost beds of the sandstone at Music Mountain, the southern terminus of Grand Wash Cliffs, about 45 miles southeast of Pierce Ferry. In central Arizona the entire formation probably lies within the Middle Cambrian.

To the north in Utah much the same situation exists, except that the sea apparently

advanced more rapidly. In the Wasatch Range of north-central Utah Walcott (1908a) applied the name "Brigham formation" to the Prospect Mountain quartzite, although he specifically states (Walcott, 1908a, p. 9) that "The Brigham formation should not be confused with the much older Prospect Mountain 'quartzite' formation of central Nevada, which is of Lower Cambrian age." Eardley and Hatch (1940, p. 828, Fig. 5), however, apparently regard the two as lithogenetically equal. Walcott assigned the "Brigham" quartzite to the Middle Cambrian on the basis of fossils in the upper part. Later Walcott (1912, footnote, p. 153) stated that the Lower-Middle Cambrian boundary lies within the quartzite at near-by Blacksmith Fork and that the section probably includes several hundred feet of Lower Cambrian beds. Deiss (1938), however, stated that "until positive evidence is disclosed, the formation should be considered Middle Cambrian only." Williams and Maxey (1941) reported lower Middle Cambrian *Albertella* and *Kochaspis* from the basal beds of the overlying Langston limestone within a few feet of the top of the quartzite. Therefore, in view of the regional thickness of the Prospect Mountain quartzite (1000 to 1600 feet in near-by southeastern Idaho—Mansfield, 1927), at least most of the formation was undoubtedly deposited during Early Cambrian time. Thus the statement of Deiss (1940, p. 788) that "there is no evidence that the Lower Cambrian sea ever invaded Montana and Idaho" appears not to be well founded.

Southward in the Tintic district, immediately west of the southern terminus of the Wasatch Range, Loughlin (1919) concluded that in view of the relationships between the local and regional stratigraphy, the top of the Tintic (Prospect Mountain) quartzite is probably very near the Lower-Middle Cambrian boundary, but that the uppermost beds may be Medial Cambrian. Because of the great exposed thickness of the quartzite (6000 feet) in the Tintic district, within which no unconformities could be found, the formation may include pre-Cambrian beds.

About 30 miles north of Tintic in the Oquirrh Range Gilluly (1932) mapped exposures of the topmost 300 feet of the Tintic quartzite and assigned these beds to the Lower Cambrian on the basis of the *Olenellus* fauna near the base (?) of the overlying shales. Gilluly (1932, p. 8) stated that "it seems fairly certain that the quartzite [of the Oquirrh Range] is to be correlated with the Tintic quartzite of the Tintic Range, and with the Cambrian quartzites of the Wasatch and House Ranges." Although Walcott (1908b) referred the basal quartzites of the House Range to the Prospect Mountain quartzite, Gilluly believes that "an attempted correlation by lithology alone is extremely hazardous, and it is by no means certain that the Prospect Mountain quartzite is the equivalent of the Tintic." Occurrence of the Prospect Mountain in the Schell Creek and Snake ranges of eastern Nevada and in the Deep Creek Range (Nolan, 1930) of western Utah supports Walcott's designation in the House Range, which also agrees with the findings of Deiss (1938). Furthermore, the regional faunal aspects of the overlying shales provide much more than mere lithologic evidence. From eastern Nevada to the Wasatch Range of central Utah, in the general latitude of the Oquirrh Range, the conformable overlying shales are both Lower and Middle Cambrian. Therefore, by a synthesis of the work of Walcott, Loughlin, Nolan, Deiss, Eardley and Hatch, and others, the Tintic and Brigham are doubtless synonyms of Prospect Mountain, and these arenaceous rocks were prob-

ably deposited throughout at least the western half of Utah and southeastern Idaho, as well as from northeastern Nevada through the Grand Canyon region into central Arizona (Pl. 2). Although lithogenetic equivalents of the Prospect Mountain quartzite are present in southwestern Nevada and southeastern California, additional stratigraphic data from southern Nevada, especially in the region of the 115th Meridian, is needed for satisfactory correlations. In this regard, Longwell's present work in the Desert Range should be revealing.

The question of the age of the pre-Pioche shale sediments of central Utah has been discussed at length by Blackwelder (1910; 1935), Hintze (1913), Loughlin (1919; 1920), Calkins (1920), Hinds, (1936), Eardley and Hatch (1940), and others. Since the present paper deals primarily with Lower and Middle Cambrian correlations, it will suffice to say that in the Wasatch Range and adjacent areas evidences of a significant break in the sedimentation of the quartzite and associated rocks have been found; quartzite is overwhelmingly predominant above the break, and phyllite, slate, schist, and tillite are fairly abundant below. Although the unconformity is by no means everywhere apparent, the sequence can usually be divided on the basis of these rock types. Where the unconformity is detected, only those quartzites above it may be designated as Prospect Mountain. For example, in Big Cottonwood Canyon only the 700 feet of quartzite above the unconformity (Pl. 2) are Prospect Mountain. In accordance with the general consensus, with which the writer agrees, strata below the break are to be regarded as pre-Cambrian. On the other hand, in areas such as the Tintic district where Loughlin reports 6000 feet of quartzite below the Pioche shale, and where no unconformity has been found, an unknown thickness at the top of the quartzite may be regarded as Prospect Mountain. Probably, as suggested by Loughlin (1919, chart facing p. 30), the lower portion is pre-Cambrian. Similarly, such an undetected unconformity may be present in other excessively thick sections such as those in the Deep Creek Range in western Utah (4750 feet) and the Snake Range in eastern Nevada (2500 feet).

PIOCHE SHALE

(Nevada, Arizona and Utah)

At its type area the Pioche shale averages about 1000 feet thick and is both Lower and Middle Cambrian. Northward at Cave Valley (Schell Creek Range) and Eureka the formation thins to about 500 and 200 feet, respectively, and at both localities apparently is entirely Lower Cambrian. In the Ruby-East Humboldt Range about 200 miles north of Pioche, Sharp (1942) reported that the Prospect Mountain quartzite lies conformably beneath Middle Cambrian limestones, with no intervening shale. Thus the northern limit of the Pioche formation in east-central Nevada is somewhere between Eureka and the Ruby Range.

About 60 miles northeast of Eureka in the Cherry Creek district on the east slope of the Egan Range, M. R. Klepper (personal communication) recently mapped and sectioned an exposure of "Pioche (?) Shale" about 2000 feet south of the Ticup mine, 3½ miles northwest of Cherry Creek. Above an unknown thickness of Prospect Mountain quartzite, Klepper measured 275 feet of purple, thin-bedded shale and argillaceous sandstone with thin calcareous beds near the top, followed by 125 feet

of platy, dark "blue" limestone with a few shaly beds, and this in turn overlain by 240 feet of green, micaceous shale, grading upward into punky, brown, micaceous sandstone with a few, thin, argillaceous limestone beds. Thus approximately 640 feet of strata questionably assigned by Klepper to the Pioche formation overlies the quartzites and underlies an unstated thickness of massive, "blue" and gray limestone.

The writer believes most of this sequence is lithogenetically equal to the Pioche shale. However, 640 feet appears to be somewhat excessive for an occurrence situated at the approximate midpoint in the triangle outlined by the Ruby Range where the shale is absent, Eureka where it measures 200 feet, and the Deep Creek Range in western Utah where its thickness approximates 500 feet. The brown, micaceous sandstones at the top of the Cherry Creek argillaceous strata may be the local equivalent of the Busby quartzite which overlies the Pioche shale in the Deep Creek Range. If so, the thickness of the Pioche formation in the Egan Range would be appreciably reduced.

Southward from Pioche the shale thins to 888 feet at Delamar, to 340 feet in the Mormon Range, and to 195 feet in the Virgin Range. It thickens to 304 feet in western Grand Canyon and thence gradually thins to the south along Grand Wash Cliffs. Except for the excessive thinning in the Virgin Range (based on Longwell's section), the thinning is gradual from Pioche southward for over 150 miles. This may indicate a possible elimination of some shale strata by faulting in Longwell's Whitney Ranch section.

Southeastward from western Grand Canyon the Pioche shale may be so designated for about 10–15 miles, where, because of the disappearance, through change of facies, of the overlying Lyndon limestone, the Pioche becomes the lower part of the Bright Angel shale.

As stated above, the Pioche shale thins to the south from western Grand Canyon along Grand Wash Cliffs. About 45 miles south of Music Mountain, at the southern end of the Juniper Mountains, Lee (1908) reports "about 225 feet" of shale above the "sandstone". This thickness, however, probably represents the combined Pioche and Chisholm shales, which, as in the Grand Canyon east of the disappearance of the Lyndon limestone, constitute the Bright Angel shale. The southerly extent of the separating Lyndon formation along Grand Wash Cliffs is unknown.

The Bright Angel shale continues to thin toward the southeast and disappears somewhere north of Jerome. Stoyanow (1936) stated that the shale thins out between Fort Rock and the Juniper Mountains, whereas R. B. Wheeler and Kerr (1936) stated that it disappears in the lower part of the Chino Valley, only about 25 miles northwest of Jerome.

The shales become progressively younger southward from western Grand Canyon. The Lower Cambrian genus *Olenellus* marks the base of the Pioche shale in the Lake Mead region, but, as stated previously, Stoyanow has found Middle Cambrian trilobites in the uppermost beds of the underlying quartzites at Music Mountain. Thus, through both faunal and facies changes, the gradual southeasterly advance of the Tonto sea into central Arizona during Early and Medial Cambrian time is clearly indicated.

At Sheep Mountain near the Goodsprings quadrangle, in southwestern Nevada

about 80 miles west of Grand Wash Cliffs, Hewett (1931) has sectioned 240 feet of Bright Angel shale above 130 feet of Tapeats sandstone. About 115 miles west of the Cliffs, in the Spring Mountains, Nevada, Nolan (1929) has mapped 1500 feet of Bright Angel above his Wood Canyon formation of quartzitic sandstones, shales, and limestone. Since the Pioche-Lyndon-Chisholm sequence now is known to be equivalent to the Bright Angel, and since these formations lie between Sheep Mountain and Bright Angel "territory", the term Bright Angel is no longer appropriate in southern Nevada. However, until more is learned of the westward extent of the Lyndon and Chisholm formations it is not possible to correlate formations between southwestern and southeastern Nevada.

Still farther west in the Nopah Range of Inyo County, California, Hazzard (1938), in apparent disregard of lithogenetic boundaries, divided the shales into two "formations" on the basis of a tentative and uncertain placement of the Lower-Middle Cambrian boundary. Hazzard placed the lower part of the shale sequence in Nolan's Lower Cambrian Wood Canyon formation and suggested that his Middle Cambrian Cadiz formation be carried eastward to include the upper part of the shales in the Spring Mountains. Thus an uncertain time-rock boundary is defined as a formational contact at the expense of logical and valid lithogenetic or mappable units.

About 120 miles northeast of the Pioche district, in the House Range of western Utah, Walcott (1908b) referred the shale above the lower Cambrian quartzite to the Pioche formation. Deiss (1938) restudied the section, measured the thickness of the shale at 265 feet, and on the basis of the presence of *Olenellus* agrees with Walcott on the Early Cambrian age of the strata and its equivalence to the Pioche shale.

In the vicinity of Pine Grove Canyon in the Wah Wah Range of southwestern Utah, about 25 miles east of the midpoint between Pioche and the House Range, Butler (1920) reported an estimated 800 to 1000 feet of shales and shaly limestones overlying massive, red quartzite and overlain by massive limestones and dolomitic limestones several thousand feet thick. Middle Cambrian fossils are listed from the shale-limestone sequence. The detrital portion of this succession represents the Prospect Mountain and Pioche formations. This occurrence aids in filling the wide gap between Pioche and the House Range. From the point of view of regional Cambrian stratigraphy, the Wah Wah section appears to be worthy of more detailed description.

About 50 miles northwest of the House Range, in the Deep Creek Range of westernmost Utah immediately north of the 40th Parallel, Nolan (1935) defined the Cabin shale above the Prospect Mountain quartzite. Two measurements of its thickness gave 493 and 530 feet. A mesonacid trilobite fragment indicates its Lower Cambrian position. Because this unit is only half as thick as Pioche shale at its type locality, and because it contains no limestone beds, Nolan applied the local name Cabin shale. The reduced thickness in the Deep Creek Range now is known to be in accord with the regional northward thinning and final disappearance of the Pioche shale, and the reduction of intercalated limestone beds is to be expected toward the east, as the Lower Cambrian geosynclinal shore is approached. Nolan disfavored correlation with the Ophir shale of central Utah because it belongs mainly to the Middle Cambrian. However, as shown in the present report, the Pioche and Ophir are for-

mationally the same, but the shales are in general progressively younger toward the east because of the gradual eastward transgression of the Cambrian sea. The Busby quartzite (Nolan, 1935) above the Pioche shale in the Deep Creek Mountains is apparently a more local expression of the detrital facies and is probably nearly contemporaneous with the arenaceous beds of the upper part of the Pioche shale and the lower part of the Tatow limestone (Deiss, 1938) of the House Range. If so, it is perhaps in part at least Lower Cambrian, rather than Middle Cambrian as presumed by Nolan.

The Ophir (Pioche) shales and slates of central Utah crop out in the Oquirrh Range (Gilluly, 1932), Tintic Range (Loughlin, 1919), and in the Cottonwood district of the southern Wasatch Range (Calkins, 1920, p. 237). Burling (1914, p. 101), 5 years before the definition of the Ophir, regarded the shale above the quartzite in Big Cottonwood Canyon as "the stratigraphic, lithologic, and faunal (?) equivalent of the Pioche formation in Nevada, and, like that formation, its first description [Walcott, 1886] listed fossils collected from Lower and Middle Cambrian zones . . . ." Of the Oquirrh Range area he stated (p. 99): "The shale near Ophir City . . . . is thus apparently the lithologic, stratigraphic and faunal equivalent of the Pioche shale in the Big Cottonwood Canyon section." To illustrate that he understands correctly the meaning of the term formation, even though a time-stratigraphic boundary may be embraced, Burling further stated (p. 124): "Under a system of nomenclature in which formations will be referable to and comparable with lithologic or stratigraphic units, the Pioche formation, from our present knowledge, appears to be an identifiable series of interbedded shales and limestones occupying a transitional zone between true quartzite and limestone series."

Most of the Pioche shale is Middle Cambrian in the Cottonwood district and in the Oquirrh Range, but the Lower Cambrian *Olenellus* fauna is reported from the basal beds at both places. In the Tintic district, however, the entire formation appears to be Middle Cambrian. The Pioche shale is also confined to the lower Middle Cambrian in the Sheeprock Range, about 15 miles southwest of Ophir (Oquirrh Range). In the Sheeprock uplift Eardley and Hatch (1940) reported *Glossopleura* and *Elrathia* from the upper beds of 100 feet of shale between the quartzite and limestone sequences.

Tintic and Sheeprock are the southernmost of these central Utah areas, and a somewhat later age of the shale at these localities is in accord with the Medial Cambrian age of the entire shale sequence in the Granite Gorge region of the Grand Canyon.

The question is now raised as to the distinction of the Pioche shale in central Utah and the Bright Angel shale in northern Arizona. In the Grand Canyon the upper portion of the Bright Angel shale is the lithogenetic equivalent of the Chisholm shale farther west. However, on the basis of sequences in the Pioche district and adjacent areas, the Chisholm shale thins rapidly toward the north and east from its type locality (Pioche district) and apparently is not present in Utah. In the absence of the Chisholm shale in central Utah, distinction of the Pioche shale there and the Bright Angel shale approximately 300 miles to the south appears impossible unless relationships with overlying formations provide conditions for the establishment of

arbitrary limits such as the boundary in the Grand Canyon between the Bright Angel shale on the east and the Pioche-Lyndon-Chisholm sequence on the west. The need for distinction, however, is not anticipated, for these Cambrian strata appear to be deeply buried beneath younger rocks throughout southern Utah and northernmost Arizona, except for the area surrounding the Arizona-Nevada-Utah corner, where the Pioche, Lyndon, and Chisholm formations are all recognizable.

In the Ogden area of the Wasatch Range Blackwelder (1910) designated an unstated thickness of shale resting upon the quartzite as Pioche shale; Burling (1914) agreed with this designation. That the Pioche shale is present throughout the Wasatch Range is indicated by Eardley and Hatch (1940, p. 836) who state that "a tripartite division (limestone, shale, quartzite) of the Cambrian . . . . extends from Dry Mountain [southern Wasatch] to Willard Canyon [northern Wasatch]."

About 25 miles west of Ogden, the southern tip of Promontory Point extending from the north shore into Great Salt Lake, Eardley and Hatch (1940) described Middle Cambrian limestone underlain by quartzite, with "little or no shale" intervening.

On Blacksmith Fork, a tributary of the Logan River, in north-central Utah, about 25 miles south of the Idaho border, Walcott (1908b) and Deiss (1938) showed the Brigham (Prospect Mountain) quartzite overlain by the Langston limestone without intervening shale. Nevertheless, Mansfield (1927) stated that "local shale beds" are present at the top of the quartzite in the Bear River Range in southeastern Idaho.

On the other hand, Williams and Maxey (1941) showed the Spence shale of northernmost Utah and southeastern Idaho to be a member within 20–25 feet of the base of the Langston formation, and not the basal member of the Ute limestone (Walcott, 1908a). The question immediately arises as to whether the Spence member, with its Chisholm fauna, is not actually the Pioche shale becoming progressively younger toward the north. In the event that these two shales should prove to be the same, the underlying "*Ptarmigania* limestone" could either be defined as a formation or grouped with the overlying shale, depending upon regional relationships.

If the Spence and Pioche shales are distinct the northern limit of the latter in north-central Utah is somewhere between Ogden and Blacksmith Fork, and somewhere south of Promontory Point.

In summary, the Pioche shale varies from Lower to Middle Cambrian and over much of its extent straddles the boundary between those series. It occurs throughout eastern and southeastern Nevada, in northwestern Arizona, and throughout most of the western half of Utah (Pl. 2).

These distributional and age relationships emphasize that the Pioche formation is to be considered a single, widespread, formational unit and that there can be no regional lithogenetic basis for its subdivision into the Pioche and Comet shales (Deiss, 1938) merely because of the local presence of the Waucobian-Albertan time-stratigraphic boundary within it. The evidence originally presented by Wheeler and Lemmon (1939) now appears conclusive that the Comet shale can have no status as a formation.

LYNDON LIMESTONE

(Nevada and Arizona)

The Lyndon limestone is thickest (350 feet) in the area of its type locality (Pioche district.) It thins to 280 feet at Cave Valley to the north and then through the northward disappearance of the overlying Chisholm shale apparently constitutes an unknown portion at the base of the Eldorado limestone of the Eureka district.

Southward from Pioche the formation thins rapidly to 102 feet at Delamar as a result of lateral change of facies, involving the overlying Chisholm shale. At Lyndon Gulch in the Highland Range the Lyndon measures 345 feet, while the overlying Chisholm has a thickness of 137 feet. At Klondike Gap near the south edge of the Highland quadrangle, the Lyndon is somewhat thinner, whereas the Chisholm thickens to 180 feet and contains limestones near the base which are typically Lyndon. About 10 miles south of Klondike Gap,[11] the massive, basal portion of the Lyndon appears to be about 100 feet thick, and the upper part consists of interbedded limestones and shales which grade into the Chisholm above; the Chisholm here appears to exceed 200 feet in thickness. This lateral gradation continues to the south, and at Delamar the Chisholm thickens to 300 feet. From Delamar southward the Lyndon limestone continues to diminish to 50 feet in the Mormon Range and 45 feet in the Virgin Range.

Still farther south in Iceberg Canyon and western Grand Canyon on Lake Mead the formation thickens somewhat with the introduction of a medial, detrital member. At the latter locality the Lyndon measures 70 feet and consists of lower and upper brown dolomites, separated by shale and sandstone. These calcareous members carry southward along Grand Wash Cliffs for at least 20 miles, and southeastward for a few miles into the Grand Canyon where they grade laterally into detrital beds. Thus to the east in the Canyon the Lyndon formation is no longer recognizable as a lithogenetic unit, and the underlying and overlying shales (Pioche and Chisholm) merge to constitute the Bright Angel shale (Pls. 1, 2).

Although the age of the Lyndon varies slightly from Cave Valley to northwestern Arizona, it appears to be lower Middle Cambrian throughout. North of Cave Valley, however, the basal beds may be Lower Cambrian as these limestones replace successively lower beds of the Pioche shale. As stated above, the Lyndon appears to constitute the lower part of the Eldorado at Eureka, and the basal Eldorado is quite certainly Lower Cambrian.

At present no attempt can be made to correlate the Lyndon and any possible lithogenetic counterparts in western Utah.

CHISHOLM SHALE

(Nevada and Arizona)

At its type locality in the Highland Range of the Pioche district, the Chisholm shale is 137 feet thick. Northward it thins to 45 feet at Cave Valley, beyond which it probably thins rapidly and disappears south of Eureka. East and northeast of Pioche the Chisholm also thins rapidly. In the Ely Range of the Pioche district,

[11] At the base of the prominent mountain about ¼ mile north of U. S. Highway 93, about 15 miles west of Caliente.

less than 10 miles east of the Highland Range, it averages only about 75 feet, whereas in the Wah Wah Range of westernmost Utah, about 60 miles northeast of Pioche, no shale is reported by Butler (1920) above those assigned to the Pioche formation. In the House Range, still farther northeast, Chisholm shale trilobites are found in the Howell limestone.

South of Pioche the shale thickens to 300 feet at Delamar, but beyond it is reduced to 275 feet in the Mormon Range, 71 (?) feet in the Virgin Mountains, and 99 feet in western Grand Canyon.

Throughout the region from Pioche to western Grand Canyon the Chisholm shale is characterized by either the *Glossopleura* or *Zacanthoides-Anoria* faunas of the lower Middle Cambrian.

BRIGHT ANGEL SHALE

(Arizona)

As stated above, a few miles east of Grand Wash Cliffs the Lyndon formation grades into detrital facies and thus becomes lithologically unrecognizable. East of the point of disappearance of the Lyndon the equivalent of the combined Pioche, Lyndon, and Chisholm formations is formationally equal to the Bright Angel shale of the Granite Gorge region. Noble (1922) showed that the Bright Angel thins to the southeast, measuring 402 feet in Garnet Canyon, 391 feet at Bass Canyon, 392 feet at Slate Creek, 344 feet at Hermit Creek, and 325 feet at Pipe Creek. In keeping with this variation, its thickness near western Grand Canyon should approximate the combined thickness of the Pioche, Lyndon, and Chisholm formations in that area (473 feet).

Because of the time involved in the marine transgression from western Grand Canyon to Nankoweap Valley, about 115 miles east, the Bright Angel shale varies from both Lower and Middle Cambrian in the west to entirely Middle Cambrian in the latter area. The overlying Muav limestone must vary similarly within Medial Cambrian time.

The above-mentioned time-stratigraphic relations are similar to those in the regions southeast of western Grand Canyon. The Lyndon formation, present on Grand Wash Cliffs 20 miles south of the canyon, appears to eventually grade out. The two shales combine to constitute the Middle Cambrian Bright Angel formation at Music Mountain, which gradually thins toward the southeast and completely disappears north of Jerome.

PEASLEY LIMESTONE

(Nevada and Arizona)

The limestones immediately above the Chisholm shale appear to belong to the Peasley formation throughout southeastern Nevada and northwesternmost Arizona. The type section of the formation is in the Highland Range, where it measures about 120 feet, although in some areas of the Pioche district it somewhat exceeds 150 feet. The unconformity between the Peasley and the overlying Burrows limestone make regional variations in Peasley thickness even more pronounced and erratic. The thicknesses are 235 feet at Delamar, more than 410 feet in the Mormon Range, and about 400 feet in western Grand Canyon. In the Granite Gorge area of the Grand

Canyon the Peasley is lithogenetically equal to an unknown thickness of the basal portion of the Muav limestone.

North of Pioche, the Peasley measures 360 feet at Cave Valley, and in the Eureka district it constitutes an unknown portion of the Eldorado limestone.

BURROWS LIMESTONE

(Nevada)

Recognition and correlation of the Burrows limestone in southeastern Nevada has presented one of the most difficult problems in these Cambrian studies. The formation was originally defined as the Burrows "dolomite" (Wheeler, 1940). Although this definition indicated that the dolomitization was believed to be secondary or epigenetic, it was learned later that the primary or limestone phase is regionally more common.

The Burrows limestone extends from Cave Valley on the north, through its type area in the Pioche district, to Delamar on the south. Its thickness is exceedingly variable in consequence of post-Burrows–pre-Highland Peak erosion. Thicknesses in the Pioche district alone range between 100 and 400 feet.

The Burrows is not recognized with certainty south of the Delamar district. This portion of the sequence is faulted out of the Mormon Range section studied by the writer, and Longwell's (1928) section from the Virgin Mountains does not differentiate such a limestone. Lithologically and stratigraphically the Mead limestone of western Grand Canyon corresponds to the Burrows, but because of the great distance (110 miles) between Delamar and the canyon Schenk and Wheeler (1942) could not be certain of the identity of these formations.

MEAD LIMESTONE

(Arizona)

The Mead limestone (Schenk and Wheeler, 1942) disconformably overlies the Peasley limestone and disconformably underlies other Middle Cambrian limestones and dolomites in western Grand Canyon. It may be the same as the Burrows limestone of eastern Nevada. At present, the Mead limestone is known only in westernmost Grand Canyon and adjacent areas along Grand Wash Cliffs.

MUAV LIMESTONE

(Arizona)

Noble (1922) described the Muav formation at Bass Canyon as 473 feet of limestone with minor quantities of dolomite, sandstone, shale, and "intraformational" conglomerate. Farther east in the Grand Canyon, Noble (1922) and Wheeler and Kerr (1936) show the Muav as thinning and becoming more arenaceous and argillaceous. The basal limestones of the Muav appear to change facies and grade laterally into the topmost strata of the Bright Angel shale. As the ultimate eastern shore of the Cambrian sea is approached in this region, the calcareous beds (Muav) may be expected to disappear completely to be replaced by detrital sediments. These rather complex time-stratigraphic relationships require more complete data from the region east of Bright Angel Creek before the limits of the Muav formation can be determined. Also, diagnostic faunas are needed from various localities to

show whether a part of the Muav is Upper Cambrian or whether the entire formation belongs to the Middle Cambrian.

The writer has shown that the Mead limestone of western Grand Canyon is disconformably overlain and underlain by Muav-like Middle Cambrian calcareous rocks and that the Mead is completely cut out by the upper unconformity a few miles east of Grand Wash Cliffs. Therefore, east of the eastern limit of the Mead limestone in this region the post-Mead unconformity lies within limestones that have previously been regarded as Muav. The question arises as to the extent of this unconformity or the pre-Mead erosion surface in the Grand Canyon. Until this problem is explored no thorough conclusions can be set forth as to the validity, extent, and relationships of the Muav limestone as now defined.

HIGHLAND PEAK LIMESTONE

(Nevada)

The complete Highland Peak limestone sequence is known only in the Pioche district. Of the 15 units (C to Q) included in Wheeler's (1940) restriction of the formation, the lower seven (C to I), which are supposedly Middle Cambrian, are all represented in the Delamar district. Except for unit D, lithologic characters and thicknesses of the Highland Peak members at Delamar are closely similar to their counterparts in the Pioche district. Unit D at Delamar is 325 feet thick, as compared with 35 feet in the type area. Probably an appreciable part of this 325 feet belongs to unit E, but their proper distinction was not noted because of local hydrothermal alteration. Furthermore, in the measured section this portion of the succession is partially repeated by a fault of unknown magnitude. The illustrated thickening of unit D between Pioche and Delamar (Pl. 1), therefore, is highly improbable, but its correction must await re-examination of the section.

The basal Highland Peak units C, D, and a portion of E are present at the east end of the Cave Valley section. Thus, portions of the formation are typically represented in southeastern Nevada from Cave Valley south approximately 100 miles to Delamar.

ELDORADO, GEDDES, AND SECRET CANYON FORMATIONS

(Nevada)

The Eldorado and Geddes limestones and Secret Canyon shale are known only in the Eureka district of east-central Nevada. Except for the underlying Pioche shale and Prospect Mountain quartzite, none of the Lower and Middle Cambrian formations so widely distributed in southeastern Nevada is lithogenetically recognizable in the Eureka area. At least some of the post-Pioche limestones exposed at Cave Valley might be recognizable at Eureka if it were not for the extensive secondary dolomitization of the Eldorado. Although the Geddes limestone is lithologically similar to unit C of the Highland Peak, nothing remotely resembling the Secret Canyon shale is known in the Middle Cambrian toward the south. To ascertain the details of these appreciable facies and phase changes, knowledge of more complete Lower and Middle Cambrian sequences is needed from the region between Eureka and Pioche.

Similar difficulties appear to be encountered in attempting correlations between

the Eldorado, Geddes, and Secret Canyon formations and the Middle Cambrian succession of the Ruby Range to the northeast. Except for the Prospect Mountain quartzite, the only similarity noted by Sharp (1942) is between argillaceous beds of the "Middle Cambrian formation" of the Ruby Range and those of the upper Secret Canyon shale at Eureka.

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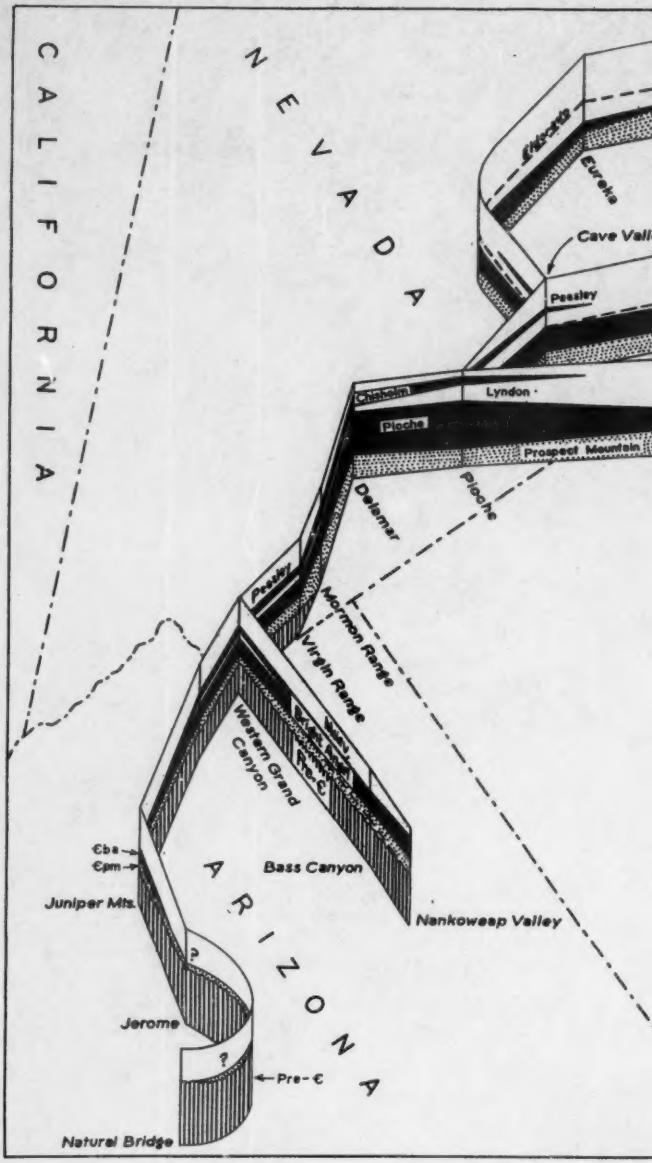
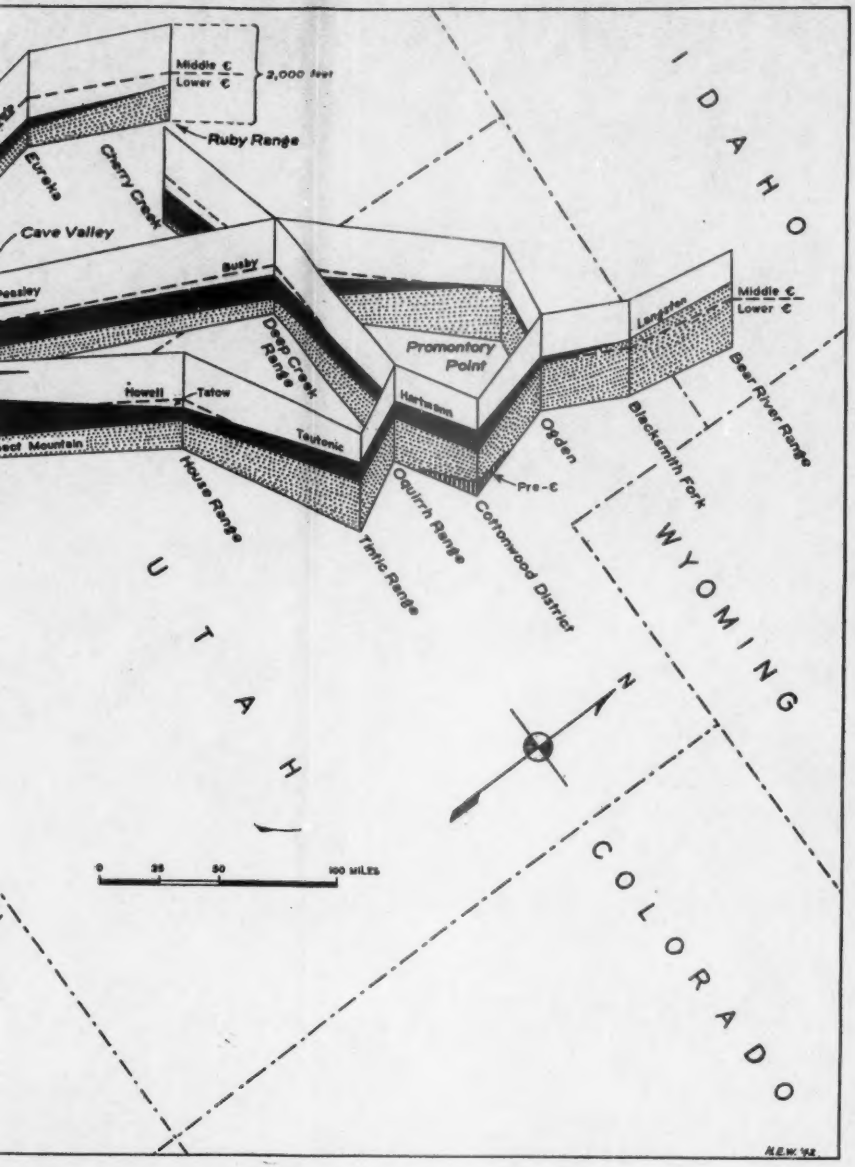


COMPOSITE C

Showing relationships of Prospect Mountain, Pioche,



POSITE CORRELATION DIAGRAM

ntain, Pioche, Lyndon, Chisholm, and Bright Angel formations in Great Basin area

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ABSTRACTS

Because the scientific meetings of The Geological Society of America and associated societies were canceled for 1943 the number of abstracts submitted is considerably reduced and in our judgment does not justify publication of the usual Part 2 of the December Bulletin.

THE GEOLOGICAL SOCIETY OF AMERICA

COWLITZ HIGH-ALUMINA CLAY DEPOSIT NEAR CASTLE ROCK, WASHINGTON*

BY VICTOR T. ALLEN AND ROBERT L. NICHOLS

The Cowlitz high-alumina clay deposit lies along the north side of the Toutle River, in the Olequa quadrangle, Washington, approximately 7 miles from Castle Rock, Washington. The investigation of this deposit was carried out jointly by the Geological Survey and the Bureau of Mines, United States Department of the Interior. Sixty-seven holes having a total footage of 5866 feet were drilled and located six ore bodies, containing several million tons of "measured ore," considerably above the minimum of 20 per cent available alumina set for high-alumina clay projects.

The high-alumina clay is interbedded with nearly flat-lying marine and continental Tertiary sediments. The ore consists of lignitic, gray, white, or greenish clay. Some of it has silty, sandy, or pebbly textures and locally contains tiny siderite nodules and some lignite. Most of the clay is semi-flint, ovaloid clay pellets are common, a small amount of the clay has been calcined by the burning of lignite, and the greatest thickness measured was 67 feet. The principal ore minerals are kaolinite, gibbsite, montmorillonite, and beidellite-nontronite.

Most of the ore rests on a water-laid breccia on which a weathering profile developed before the deposition of the clay. The high-alumina clay is mainly of sedimentary origin. It is in part a stream deposit, in part a swamp deposit, and some of it, especially the fine-grained facies, may be lacustrine. Some of the clay may have been derived from that part of the weathering profile, developed on the breccia and probably on other rocks, which was outside the area where the clays were deposited. The presence of decomposed sands and silts and of gibbsite indicates that residual weathering, in part under a warm moist climate, was also a factor in the development of the deposit.

PLEISTOCENE BOULDER GLACIER, BEARTOOTH MOUNTAINS, MONTANA

BY ARTHUR BEVAN

Boulder Glacier in the Beartooth Mountains occupied much of Boulder Valley, tributary to Yellowstone Valley at Big Timber, 35 miles east of Livingston, Montana. This north-trending valley, 60 miles long, heads on the high divide 10 miles north of Yellowstone Park. The southern half is a canyon, 3000–4000 feet deep, cut in the subsummit plateau. North of the range the valley is somewhat broader and is bordered by high cliffs capped by terraces.

Boulder Glacier was supplied chiefly by large tributaries—one in a large frying-pan basin—from the west, which originally headed along the east side of the West Boulder (subsummit) plateau. Notable contributions were made also by a few large tributaries from the east, toward the head of Boulder Valley. Some supply was received from that part of the Beartooth ice field just north of Yellowstone Park, but the extent of this contribution is yet undetermined.

Boulder Glacier was about 40 miles long. It extended about 12 miles north of the range front, in places overtopped the divides on both sides of the valley, and stopped at an altitude of about 4800

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feet. A frontal lobe spread eastward over a low divide into the East Boulder-Elk Creek basin. A few miles south of the canyon mouth, huge drift boulders are now at an altitude of 7500 feet, or 2200 feet above Boulder River. Similar boulders were deposited in ponded tributary valleys on the west side of the glacier.

Various criteria suggest that Boulder Glacier was contemporary with the largest late Pleistocene glaciers of the northern Rocky Mountains, presumably during the Bull Lake stage. (Geological Society project.)

RADIOLARIA FROM THE KREYENHAGEN FORMATION NEAR LOS BANOS, CALIFORNIA

BY BRUCE L. CLARK AND ARTHUR S. CAMPBELL

A series of Radiolaria are described from the Kreyenhagen shales as found along the west side of the San Joaquin Valley in the Charleston School quadrangle near Los Banos, California. These deposits are about 700 feet thick and are dominantly organic shales. The samples were obtained from 12 stratigraphic horizons. One hundred four species are represented, a considerable number of which were originally described from the Sidney and Kellogg shales from the Mount Diablo and Byron quadrangles. The conclusion is that the zone represented by the Sidney shale is not represented in this section. The faunas from the lower assemblages suggest a fairly close relationship to those found in the Kellogg shales which are just below the Markley formation of the Mount Diablo area and that the other assemblages are probably intermediate between the Kellogg and the Sidney shales. (Geological Society project.)

LOWER MIDDLE ORDOVICIAN ALONG CLINCH MOUNTAIN IN VIRGINIA AND TENNESSEE*

BY BYRON N. COOPER

Faunal and lithologic studies of the lower Middle Ordovician succession between Burkes Garden, Tazewell County, Virginia, and Luttrell, Union County, Tennessee, show that:

(1) The Moccasin, Witten, and Bowen formations persist without much change throughout the Clinch Mountain belt (165 miles).

(2) Beyond the southwestern limits of the Gratton limestone, in Tazewell County, Virginia, the Wardell formation directly succeeds the Benbolt limestone; the two are readily distinguished as far southwest as Eidson, Tennessee, but at Thorn Hill and Luttrell their boundary is less distinct.

(3) The Wardell, unlike the Benbolt, abounds in bioherms and biostromes, composed of stromatoporoids, corals, sponges, and calcareous algae.

(4) The Benbolt becomes increasingly shaly toward Speers Ferry, Scott County, Virginia; between Hansonville, Virginia, and Eidson, Tennessee, it is richly fossiliferous.

(5) Southwest of Tazewell County, Virginia, dark bluish-gray cherty limestones in the Cliffield interfinger with coarse pinkinsh calcarenytes (Holston-type limestone). Where the calcarenytes are thickly developed, members of the Cliffield recognized in Tazewell County, Virginia, are not readily distinguishable, except for the *Dinorthis atavoides-Sowerbyites triseptatus* zone which persists at least as far southwest as Eidson, Tennessee.

(6) In Russell County, Virginia, the zone of basal clastics of the Blackford member has intercalations of pinkish Holston-type limestone which contain rhynchonellid brachiopods like those in the type Lenoir of Tennessee.

(7) Age relations of lithologically dissimilar sections of the lower Middle Ordovician in the Clinch Mountain belt have been established through fossils and by recognizing several chronologically equivalent facies of limestone, notably calcilutytes and calcarenytes.

GLACIAL GEOLOGY ALONG THE ALASKA MILITARY HIGHWAY, DAWSON CREEK, BRITISH COLUMBIA, TO WHITEHORSE, YUKON TERRITORY

BY C S. DENNY

A dissected plateau covered with pebbly clay till extends from the Peace River, British Columbia, northward for 250 miles to Fort Nelson. Varve clays occur in the major valleys which dissect this

* Published by permission of the State Geologist of Virginia.

plateau, such as along the eastward-flowing Beatton and Sikanni Chief rivers. Clays are probably also present in the lowlands between the plateau and the Rocky Mountains to the west, as along the Prophet River for 100 miles south of Fort Nelson. Erratic pebbles presumably from the Canadian Shield are found throughout this region, especially along the Prophet and Musqua rivers near Fort Nelson and westward for 50 miles.

From Summit Lake, 100 miles west of Fort Nelson, to the Liard River there are mountains indented by glacial cirques and cut by U-shaped valleys. These valleys are narrow gravel plains, bordered in places by alluvial fans or narrow outwash terraces. Small glaciers are visible 10 to 20 miles southwest of the Highway.

The Liard River above the canyon follows a narrow flood plain incised below a kettled outwash terrace. Near Watson Lake, a broad lowland of rolling bouldery till-covered hills and kettled outwash plains is dissected by the Liard and its tributaries.

In the Rancheria-Swift River drainage, narrow U-shaped valleys contain small outwash terraces and are bordered by low mountains, some of which are indented by cirques.

The large lakes and rivers from Teslin to Whitehorse are surrounded in some places by kettled outwash plains and elsewhere by lacustrine silt and clay. (Geological Society project.)

INTRUSIVES IN SOUTHEASTERN ONTARIO

BY J. M. HARRISON

A detailed description is given of certain anorthosites, gabbros, and associated rocks in southeastern Ontario. From evidence obtained in the field, and with the microscope, it appears that the anorthosites formed from a magma with a composition about that of gabbroic anorthosite. It is suggested that the more mafic masses occupy a position higher in the earth's crust than do the anorthosites. Concentration of dark minerals was probably caused in part by rising volatile-rich fluids carrying such elements as iron and titanium and in part by assimilation of limey sediments by the magma. The source of the magma may have been a layer in the earth's crust with a composition approaching that of bytownite anorthosite. There are granites of two ages separated by the period of intrusion of the basic rocks.

SCABLANDS GLACIAL LOBE IN EASTERN WASHINGTON

BY WILLIAM H. HOBBS

A hitherto unsuspected southwestward extension of the Cordilleran glacier of Late Pleistocene time has been established by studies in 1943. This extension of nearly 4000 square miles is the area of so-called "Scablands" in eastern Washington.

Hitherto the glacier front was thought to have been in the latitude of Spokane. The newly discovered extension is heart-shaped and is called the Scablands Glacial Lobe.

On the east this lobe blocked an ancestor of the Spokane River, which was much swollen by glacial meltwater, to impound the waters over an area of some 3000 square miles as Glacial Lake Spokane. This lake had an outlet along the eastern and southern border of the lobe, and successive spillways into the Columbia and Snake rivers were through Esquatzel Coulee and Devils and Palouse canyons.

Six major recessions of the lobe have been made out with the new outlets for Lake Spokane successively westward through other canyon spillways into the Columbia River.

The main outwash apron of the Scablands lobe was the eastern portion of the Columbia Basin. Outside and peripheral to it is the contemporaneous apron of loess, which studies of the Greenland glacier have shown should always be found within the periglacial area of a continental glacier.

Complete evacuation of the ice of the Scablands with the retirement of the glacier front behind the Spokane and Columbia Rivers brought about an expansion of Lake Spokane down the canyons of these rivers. This has been named Glacial Lake Leverett. It was blocked by ice below the site of Coulee Dam and it cut an outlet through the Grand Coulee This outlet is a double cataract gorge like that of Niagara, but five times as high and many times as wide—the greatest feature of the kind anywhere known. (Geological Society project.)

TWO TILLS IN THE CONCORD QUADRANGLE, MASSACHUSETTS

BY JOHN HALL MOSS

Field work in the Concord quadrangle, Massachusetts, revealed the presence of Old and New till having notably different characteristics. The Old is found in the drumlins and in deep pits in the interdrumlin areas. The New till forms a 3- to 12-foot veneer on the Old. The Old till is dark gray, weathering to muddy brown, is highly compact, breaks into "clumps," has a moderate proportion of rotted boulders, and shows an obscure undulating cleavage. The New till is light gray, weathering to buff, is loosely packed, easy to excavate, does not break into "clumps," has fewer rotted boulders, and no cleavage. Laboratory tests on 26 samples of the tills taken from either side of contacts revealed further differences: (1) Cumulative weight curves of Old lie above New for grain sizes smaller than .69 mm. Old till median diameter size is 5–15 mm. smaller than New. (2) Old till has 6–18 per cent more particles by weight finer than .07 mm. and 2–7 times as much clay-size material as the New. (3) New till has 2–4 times as many cobbles which cannot be broken or chipped by impact of a 7-pound force moving with a momentum of 3.2 slug-feet per second. (4) Old till is oxidized to at least 3 times as great a depth and where it directly underlies New has a notably greater limonite content as revealed by measurement with a colorimeter. (5) Pebble counts show petrographic differences.

These differences between the tills are best explained by postulating two ice advances during Wisconsin time separated by a brief interglacial or interstadial epoch.

MACROFOSSILS FROM WELLS ON THE ATLANTIC COASTAL PLAIN

BY HORACE G. RICHARDS

Macrofossils in samples from about 170 wells along the Atlantic Coastal Plain between New Jersey and Florida have been studied. While many of the wells contained few fossils of special interest, or none at all, certain wells have revealed information of particular stratigraphic or paleontological significance:

(1) Fragmentary marine fossils in the Cretaceous Englishtown sand (hitherto regarded as unfossiliferous) in wells at Fort Dix, and Asbury Park, New Jersey.

(2) A Jacksonian fauna in a well at Brandywine Lighthouse in Delaware Bay, New Jersey.

(3) Upper Cretaceous fossils from wells at Norfolk, Drivers, and Franklin, Virginia, suggesting a correlation with the Eagle Ford formation of Texas.

(4) Two marine fossils from a well at Franklin, Virginia, suggesting the possible presence of Paleocene Midway deposits.

(5) Marine fossils from the Cretaceous Tuscaloosa formation, particularly from wells at Parris Island, South Carolina, and near Albany, Georgia. Near Albany the Tuscaloosa is apparently about 2500 feet thick.

About 20 new species have already been recognized. The study is being continued. (Geological Society project.)

NEW APPLICATION OF EN ECHELON TENSION FRACTURES TO GEOLOGICAL STRESS-STRAIN ANALYSIS

BY VINCENT E. SHAININ

Abundant experimental and field evidence shows that en echelon tension fractures are formed under rotational strain as ruptures normal to maximum elongation.

The lower Ordovician argillaceous Athens limestone at Riverton, Virginia, exhibits pinnate tension fractures aligned, en echelon, in fairly straight rows of up to 50 fractures. The trends of the rows of conjugate sets are east-west and northwest-southeast, forming an angle of about 40°. The shearing couple origin of echelon fractures suggests that the trend of each row may be considered as the trace of a plane of incipient shearing. Some shear fractures parallel the trend of a row. The acute angle between the conjugate incipient shear planes always faces the direction of greatest shortening (the greatest stress axis).

The axis of elongation in the case of the incipient shear planes is essentially horizontal, while that of the folds and thrust faults of the area is essentially vertical. However, the axes of shortening practically coincide, which suggests that the direction o f greatest stress was essentially the same.

Two hypotheses are advanced: (1) As in the deformation of a prism in Daubrée's classic experiment, two sets of conjugate shears developed simultaneously as the result of one compressive stress. Direction of elongation for one set of shears, however, was normal to that for the other. (2) There were two periods of compressive stress, each accompanied by a different direction of elongation. A modification of this hypothesis postulates that the similarity in orientation of the greatest stress axes at Riverton is a local coincidence and that a regional survey might show a change in the direction of axes of greatest stress.

ORE DEPOSITS OF THE JOPLIN (TRI-STATE) REGION

BY W. S. TANGIER SMITH

This paper presents a variety of evidence all indicating an artesian rather than a magmatic origin for the zinc-lead ores of the Joplin region.

Ore deposition began while the ore-bearing breccias of the Boone formation were beneath the margin of the Pennsylvanian shale. As the shale margin retreated westerly through erosion, new deposits formed successively beneath the shale, while the older deposits emerged. The age of the ore bodies therefore increases toward the east.

The first stage of ore deposition, that beneath the shale, is characterized by replacement of the limestone of the breccias by jasperoid, dolomite, and sphalerite, and by the deposition of sulphides in cavities. With the emergence of the Boone formation with its ore bodies from beneath the shale, a second or intermediate stage of ore deposition ensued, owing to changes in the character of the ore solutions. This stage was marked by cessation of limestone replacement and by continued deposition of ore in cavities, together with calcite. Ore-body alteration also begins during this stage, and with increasing distance from the shale margin the effects are cumulative, until, east of Joplin, alteration becomes the dominant factor and marks the third stage in the evolution of the ore bodies.

The paper also shows that certain evidence offered by other writers, especially by Graton and Harcourt and by Newhouse, has led to erroneous conclusions because of the limitation of their investigations to the primary ores.

UPPER CRETACEOUS AGE OF THE "FRANCISCAN" LIMESTONE NEAR LAYTONVILLE, MENDOCINO COUNTY, CALIFORNIA

BY HANS E. THALMANN

Microscopic study of a reddish, slightly siliceous limestone, collected by N. L. Taliaferro in 1939 from outcrops about 200 yards east of the Redwood Highway, 2 miles north of Laytonville, Mendocino County, California (Stanford Univ. Coll. Sta. M-375), disclosed the presence of a foraminiferal assemblage consisting of *Globotruncana renzi* Thalmann, *Globigerina cretacea* d'Orbigny, small *Gümbelina* sp., *Bolivina* sp., *Astacolus ?* sp., *Nodosaria* sp., *Rotalia ?* sp., and other difficultly identifiable forms. The *Globotruncana* species is abundant in all sections made from this limestone and clearly indicates at least a Turonian age for the so-called "Franciscan" limestone at Laytonville.

The Laytonville limestone, therefore, is to be regarded as a synchronous deposit of the Calera limestones of the quarries of the Permanente Cement Company, Santa Clara County, and of the Calera limestone at its type locality in Calera Valley, San Mateo County, California. Identical foraminiferal assemblages of Turonian age have also been detected in the Calera limestone outcropping between Bolinas and Olima, Marin County, California, and in the Whitsett limestone at the south fork of Deer Creek, and on a branch of Roberts Creek, Douglas County, Roseburg quadrangle, Oregon. All these limestones, hitherto placed in the Franciscan formation and regarded as Upper Jurassic, must now be attributed to the Upper Cretaceous (Turonian stage).

This new age assignment of several limestone intercalations in the Franciscan formation is likely to throw a new light on the geological history of the Franciscan-Knoxville geosyncline in California

UPPER CRETACEOUS LIMESTONES NEAR SAN JUAN, PROVINCE OF CHIMBORAZO (WESTERN ANDES), ECUADOR

BY HANS E. THALMANN

Since fossiliferous Mesozoic sediments are extremely rare in the western Andes of Ecuador, it is interesting to note the presence of a fairly rich foraminiferal assemblage in gray and grayish-brown

limestones collected in 1940 by Dr. J. J. Dozy (Quito). These limestones, examined in thin sections, revealed the occurrence of abundant *Siphogenerinoides* of the *S. ewaldi* (Karst.) and related types, associated with sections through tests of *Bathysiphon, Gumbelina, Bolivina, Textularia, Globigerina, Dorothia, Palmula*, lagenids, miliolids, polymorphinids, Bryozoa, etc. Fragments of tests (with embryonic chambers) of either *Lepidorbitoides(?)* or *Orbitocyclina(?)* and a single section through a *Globotruncana* specimen of the *G. stuarti* (de Lapparent) type have also been observed in several thin sections and on the polished surface of rock specimens. The presence of Orbitoididae is paleogeographically of great interest.

The locality of the limestone outcrops is about 4.2 km west of the village of San Juan, on the Riobamba-Guaranda road, Chimborazo Province, Ecuador. Gray limestones and dark slates are tightly folded, dip steeply westward, and form a thick series of sediments which extends westward beyond Hacienda Santa Rosa for at least 10 to 12 km.

Based on foraminiferal evidence the San Juan limestone is probably Upper Campanian or Maestrichtian in age and, therefore, approximately equivalent to the upper Palmira series (Guadalupe and Umir formations) of Colombia, the upper Cretaceous Rimac formation of the western Cordillera of Peru, and the upper Cretaceous Tena formation on the eastern side of the Ecuadorian Andes.

Siphogenerinoides limestones of identical age, but without orbitoids and with a poorer assemblage of concomitant Foraminifera, are known also from outcrops along the road between Calacali, Yungilla, and Nanegal, about 25 to 30 km north-northwest of Quito, Ecuador.

RECONSIDERATION OF THE MORRISON FORMATION IN THE TYPE AREA, JEFFERSON COUNTY, COLORADO

BY W. A. WALDSCHMIDT AND L. W. LEROY

The section of the Morrison formation which is recommended as the "type" has been selected not only because it is exposed in its entirety along the West Alameda Parkway Roadcut, 2 miles north or Morrison, Colorado, but also because it is readily accessible. At the recommended type section it is a distinct cartographic unit which can be subdivided into six parts primarily on the basis of lithologic characteristics of the sedimentary rocks.

Fossils in the Morrison formation are confined to three horizons. Dinosaur remains are abundant in basal sandstones of the gray shale and sandstone unit. Probable fresh-water sponge spicules are plentiful throughout an interval of 25 feet in the central part of the gray clay and limestone unit. A few spicules, however, are also present from 2 to 6 feet above the dinosaur-bearing sandstone. *Aclistochara*, the occurrence of which has not been reported previously from the Morrison formation, is relatively abundant in the upper 30 feet of the gray and red shale unit. This would place the highest occurrence of *Aclistochara* 63 feet above the base of the Morrison formation.

The results of copper nitrate staining of samples from the calcareous rocks of the Morrison formation indicate that the greatest amount of calcite is present in the gray clay and limestone unit. The distribution and intensity of copper nitrate stains could probably be used effectively in connection with petrographic studies to identify several strata within the Morrison formation.

THE PALEONTOLOGICAL SOCIETY

CORYNOTRYPA FROM THE UPPER PENNSYLVANIAN OF NEBRASKA

BY G. E. CONDRA AND M. K. ELIAS

A new species of *Corynotrypa* is found adnate on *Pinna* from the Shawnee and Wabaunsee groups in Nebraska. Previous range of the genus from the lower Ordovician to the Devonian is thus extended to the top of the Pennsylvanian, but it remains unknown in the Mississippian.

DOUBLEBASKET-LIKE BRYOZOAN-ALGAL CONSORTIUM OF PERMIAN AGE

BY G. E. CONDRA AND M. K. ELIAS

A new bryozoan-algal symbiotic consortium is recorded from the Kaibab limestone at Grand Canyon, Arizona. It consists of a basket of *Polypora* type thickly encrusted from behind by algal tissue and interconnected with an inner, less regular, basket built by the same algal tissue and parallel to the outer basket. The algal meshwork resembles that of the living red algae *Liagora* and, particularly, *Marchesettia spongiodes*, which lives in a consortium with a sponge.

HEDERELLA FROM THE LOWER AND MIDDLE PENNSYLVANIAN OF THE MIDWEST

BY G. E. CONDRA AND M. K. ELIAS

A new species of *Hederella* is recognized in the Oquirrh formation of Des Moines (Lower Pennsylvanian) age at Stockton, Utah, and in beds of Missouri and Des Moines series of Oklahoma. These are the highest occurrences of this adnate bryozoan genus known to date.

OCCURRENCE OF THE RUSSIAN GENUS RHOMBOTRYPELLA IN THE LOWER PENNSYLVANIAN OF UTAH

BY G. E. CONDRA AND M. K. ELIAS

Three new species of *Rhombotrypella*, a Russian late Paleozoic genus, are recognized in collections from the Oquirrh formation of Des Moines (Lower Pennsylvanian) age near Stockton, Utah. The core of the zoarium with rhombically arranged zooecia is surrounded by a zone of the same kind turned diagonally at 90°, and by the outer, or cortical tissue. Resemblance to three similar layers of zooecial tissue in *Rhombotrypa* may indicate true relationship to this Silurian genus, and the South American Carboniferous *Rhomboporella* may prove to belong to the same group.

OSTRACODE MOULTING IN A SPECIES OF ECTODEMITES

BY CHALMER L. COOPER

During the examination of several collections of ostracodes from the lower Marble Falls (Upper Morrow age) formation of Texas, three specimens of a new species of *Ectodemites* were observed to have smaller shells of the same species attached along the hinge line. The smaller carapaces were suspected of being moults, and, to test this hypothesis, all specimens of the species in the sample were picked and arranged according to size. These were measured and the results plotted on graph paper, with the length and height as co-ordinates. The points thus obtained were found to be arranged in eight groups, the mean of each group lying on a straight line. The position of the points for the large shells and the smaller ones attached to them coincides with the last two groups, indicating that these double specimens represent the largest adult with its last moult.

The spacing of the mean points of each moult along the straight-line curve is not regular but varies in a regular manner, so that when plotted against the mean length of the moults an expanding sine curve is obtained. The implications of this variability are not fully understood at present but it suggests biennial moulting, the fall moult, after a season of plentiful food, being the largest. Another interesting feature of the straight-line curve is that the form ratio (length/height) of this species is constant from youth to adulthood; otherwise the curve would not be straight

AULOPORIDAE AND HEDERELLA; MORPHOLOGY AND TAXONOMY

BY MAXIM K. ELIAS

The morphology of the late Paleozoic Auloporidae, though comparatively simple, became only gradually clearly understood, while the taxonomy of these tabulate corals became complicated.

The essential features of distinction are summarized for the following coral genera: *Aulopora*, *Cladochonus* (=*Monilopora*), and *Aulocaulis*, and for the bryozoan *Hederella*, which is externally similar to them.

The suggestion is made to use symbolic characters (Greek letters) in front of fossil generic names whenever it is desirable to indicate in which particular sense the generic name is used: as a natural genus, a form genus, a "utilitarian" genus, or a composite genus.

PALAEOCORYNE AND RELATED EPIZOIC ALGAE OF LATE PALEOZOIC AGE

BY MAXIM K. ELIAS

Limestone (probably the Great Blue) of Mississippian age is exposed at Flux, on the southern side of Great Salt Lake, Utah. G. E. Condra and the author found here several species of the British genus *Palaeocoryne* attached to the poriferous side of *Fenestella*, mostly *F. nodulosa*, a British lower Carboniferous bryozoan. A new genus, related to *Palaeocoryne*, is attached to the poriferous side of and spreads its repeatedly bifurcating branches closely above *Fenestella plebeia*, also a British species of the same age.

Another related epizoic genus of simpler, spine-bearing columnar structure, known to British paleontologists as "spiniferous processes" on *Fenestella*, was also obtained at Flux and at many horizons and localities throughout the Midwest ranging from the Keokuk of Illinois to the Leonard of Texas; it is attached to the edges and reverse of various species of *Fenestella*.

These three genera of the epizoic algae are closely comparable to the hooked branches of the living red alga *Asparagopsis armata*.

MIDDLE DEVONIAN NAUTILOIDS OF NEW YORK

BY ROUSSEAU H. FLOWER

Descriptions and illustrations of new and many old species are presented. Faunal lists are supplied for the Lower Devonian formations and the Schoharie. No single Onondaga fauna is found. Instead there are the following faunules: (1) a lower Onondaga fauna of western New York and Ontario, continued by the Eversole chert of Ohio, containing types reminiscent of the Schoharie, (2) an upper Onondaga fauna of western New York having much in common with the upper beds of the Columbus limestone; (3) a series of localized sporadic occurrences of Rutoceratidae from Schoharie to the Genesee Valley. The Cherry Valley fauna is summarized, and new forms are described. Close relatives of Cherry Valley species, without counterparts in the Onondaga, occur in the Columbus, suggesting that its upper beds may extend into the lower Hamilton. The Solsville and Stafford contain characteristic assemblages. Two faunas characterize the later Hamilton. The Skaneateles fauna, consisting largely of Pseudorthoceratidae, can be traced upward into the Ludlowville and is modified in the Moscow, the cephalopods appearing to spread westward as they are traced upward. The Ludlowville of Lake Erie contains a fauna distinct from the Skaneateles but contributes in part to the Moscow.

The cephalopods of the New York Devonian are placed in the Michelinoceratidae, Pseudorthoceratidae, Rutoceratidae, Rhadinoceratidae, Brevicoceratidae, Centroceratidae, and Sactoceratidae, while a few breviconic genera remain of uncertain position. The relationship of Tully and higher cephalopod faunas is discussed.

ORDOVICIAN CEPHALOPODS OF THE CINCINNATI REGION

BY ROUSSEAU H. FLOWER

Systematic treatment of the Cincinnati cephalopods involves 12 families, 40 genera, and about 150 species. Evolution and geographic range of the genera and families in the Ordovician are outlined, forming a background for the re-examination of the concepts of faunal origins of the Cincinnatian forms. Ohio, Ontario, and New York yield an indigenous fauna of *Treptoceras* and *Endoceras*, with few other types. Other genera represent short-lived incursions of exotic faunas. The Cynthiana-Cathys association, contributing a few types to the Eden, and modified in the Leipers, shows few recognizable austral types, and unexpected Anticosti, Lyckholm, and boreal affinities. A limited incursion of *Ecdyceras* and *Probillingsites* marks the Arnheim of western Kentucky. Other "Rich-

mond" genera occur in the lower and middle Waynesville but disappear in the Blanchester and Liberty. They reappear in the lower Whitewater with types new to the region. Saluda, upper Whitewater, and Elkhorn cephalopods are closely allied but often not conspecific with the lower Whitewater.

No species of the Cincinnati arch is known from other regions. Genetic affinities suggest connections between the Cincinnati sea and the arctic seas as early as Cynthiana time. The probable role of climatic and ecological factors does much to lessen the stratigraphic significance of many supposedly "Richmond" genera and to strengthen the possibility that those genera may have appeared much earlier in other regions.

AUSTRALIAN HYDROZOAN GENUS, ARCHAEOLAFOEA, AND EUROPEAN BRACHIOPOD GENUS CHONETOIDEA, IN THE ORDOVICIAN OF NEW YORK

BY B. F. HOWELL

A new species of *Archaeolafoea*, a genus of Hydrozoa previously known only from the Middle Cambrian of Victoria, Australia, and a new species of *Chonetoidea*, a genus of Brachiopoda previously reported only from the Upper Ordovician and Lower Silurian of Wales, have been found in the Ordovician Schenectady formation of New York. They will be described in the Bulletin of the Wagner Free Institute of Science.

BURROWS OF FORALITES FROM THE CAMBRIAN OF THE CHAMPLAIN VALLEY

BY B. F. HOWELL

The generic name, *Skolithos*, should be used only for burrows all of which are perpendicular or almost perpendicular. Such burrows may have been made by phoronids. The generic name, *Foralites*, proposed by Rouault in 1850, should be used for burrows most of which are curved or penetrate the beds diagonally and which have an aperture at the surface and are relatively short and are definitely terminated at the other end. Such burrows were inhabited by marine worms. Rouault described two species of *Foralites* from the Lower Ordovician Armorican beds of Brittany. Another species, which the author will describe, occurs in the Upper Cambrian Theresa beds of northeastern New York.

NEW UPPER CAMBRIAN FAUNAS FROM PENNSYLVANIA

BY B. F. HOWELL

Early Late Cambrian, Dresbachian, fossils occur in Bucks County, Pennsylvania. Four distinct faunas and one flora appear to be represented. Genera represented are: of calcareous algae, *Cryptozoon* and *Dolatophycus;* of brachiopods, *Lingulella*, *Lingulepis*, and *Dicellomus;* of trilobites, *Pemphigaspis*, *Welleraspis*, *Talbotina*, *Coosia*, *Coosella*, *Lonchocephalus*, *Genevievella*, and a new, as yet undescribed, genus; and of conchostracans, *Indianites*. Late Late Cambrian, Trempealeauian, fossils have been found in Northampton County, Pennsylvania. Genera represented are: of calcareous algae, *Anomalophycus;* of brachiopods, *Lingulella* and *Lingulepis;* and of trilobites, *Saratogia*, *Calvinella*, *Tellerina*, and *Plethometopus*.

APTIAN LOWER CRETACEOUS FORAMINIFERA AND OSTRACODA FROM SAN JUAN RAYA, PUEBLA, MEXICO

BY FRANK E. LOZO, JR.

The Upper Aptian fauna studied consists of an assemblage collected by W. S. Adkins from the zone of *Phylloceras rioi* Nyst and Galleoti (*see* C. Burckhardt and F. G. K. Mullerried, Eclogae geologicae Helvetiae, vol. 29, no. 2, p. 318, 1936). The Foraminifera are represented by species of *Pseudocyclammina*, (?) *Choffatella*, *Flabellammina*, *Ammobaculites*, *Nodosaria*, *Dentalina*, and *Textularia*. Ostracode genera represented are tentatively identified as *Metacypris*, *Cytheridea*, *Cytheropteron*, *Cythereis*, *Cytherelloidea*, and *Paracypris*. The affinities of this fauna indicate a close relationship to the warm and shallow-water facies represented in the Mediterranean region by deposits in Portugal, Spain, Switzerland, and southern France.

FORAMINIFERA AND OSTRACODA FROM THE CUCHILLO (LOWER CRETACEOUS) FORMATION, QUITMAN MOUNTAINS, TEXAS

BY FRANK E. LOZO, JR.

The material examined is from the Lower Albian zone of *Douvilleiceras mammillatum* (Schlotheim) as exposed in Mayfield Canyon and 4 miles northeast of Indian Hot Springs, Hudspeth County, Texas (localities M1 and M2 of Gayle Scott, University Texas Pub. 3945, p. 981, fig. 139, 1940). Although incompletely studied, the assemblage from the fossiliferous gray marls is remarkably similar to that from the lower portion of the Rodessa and upper portion of the Pine Island formations of the East Texas Embayment area. It is believed that the Quitman Mountains assemblage is contemporaneous with the subsurface eastern Texas—northern Louisiana assemblage.

LATE EO-TRIASSIC FAUNA IN THE CANYON OF LIARD RIVER, B.C., CANADA

BY F. H. MC LEARN AND E. D. KINDLE

A late Eo-Triassic fauna was found by E. D. Kindle, Geological Survey of Canada, during the past field season, on Liard River. It includes ammonites tentatively referred to the genera *Wasatchites* and *Xenoceltites*. It occurs in the same formation as, but apparently at a lower horizon than, the fauna with *Nathorstites*, collected by R. G. McConnell in 1887.

DECAPOD CRUSTACEANS FROM THE CRETACEOUS OF TEXAS

BY H. B. STENZEL

Cretaceous strata of Texas contain a rich crustacean fauna. Species of the genera *Linuparus*, *Astacodes*, *Enoploclytia*, *Homarus*, *Galathea*, *Upogebia*, *Pagurus*, *Notopocorystes*, *Necrocarcinus*, and *Cenomanocarcinus* are described. One new genus is proposed, and a new species of that genus is described from the Grayson marl (Cenomanian). In many instances the copious material at hand made it possible to straighten out misconceptions of previously described, less complete material, notable examples being *"Nephrops" americanus* Rathbun and *Callianassa gamma* Rathbun.

NEW CRETACEOUS CRAB FROM MEXICO

BY H. B. STENZEL

The first species of the genus *Graptocarcinus texanus* Roemer was described in 1887 from the lower Cenomanian Buda limestone of the neighborhood of Austin, Texas.

The new species is the second of the genus and was obtained by the late John M. Muir from the Taninúl limestone (Albian) of the Choy Cave in Sierra del Abra, State of San Luis Potosí, Mexico.

NEW PALEOCENE CRAB FROM TEXAS

BY H. B. STENZEL

The square-fronted or catometope crabs are a loosely combined group of crabs which have usually a carapace of squarish outline. However, the group is ill-defined as a whole and not sharply separated from the cyclometope or round-fronted crabs. The family Goneplacidae in particular is a link between the two groups. Perhaps in this family shall be found the ancestors of the catometope crabs. In this respect the new genus is obviously important, because it is a very ancient goneplacid.

The genus is based on a species collected from the Wills Point formation, Midway group, of Tehuacana Creek, Limestone County, Texas, and is related to the recent genus *Pilumnoplax* Stimpson.

ANTILLESINA GALLOWAY AND HEMINWAY AND CRIBROPULLENIA THALMANN

BY HANS E. THALMANN

In their monograph of the Tertiary Foraminifera of Puerto Rico, Galloway and Heminway (1941) erected a new genus, *Antillesina*, with *Nonion ? marielensis* Palmer, 1936, as genotype. Thalmann

proposed a new generic name, *Cribropullenia* in 1937, with exactly the same species as genotype, questionably referred to *Nonion* by Mrs. Palmer, and evidently regarded by her as a probable new generic type. *Antillesina* Galloway and Heminway, therefore, becomes a synonym of *Cribropullenia* Thalmann.

This genus is represented by two distinct species: the genotype *Cribropullenia marielensis* (Palmer), recorded from the lower Oligocene in the Pinar del Rio province of Cuba, from the middle Oligocene San Sebastian formation, and from the Oligo-Miocene Ponce formation of Puerto Rico, and *Cribropullenia obscura* (Schwager), originally described as *Polystomella ? obscura* by Schwager (1883) from the Eocene (Libyan stage, *Operculina* horizon) of El Guss Abu Said, Oasis Farafrah, Egypt.

The generic characteristics are: costate and tumid chambers, and porous, cribrate aperture. Two other species of the *Nonion* type show a typical cribrate aperture, namely *Nonionina heteropora* Egger (1857) and *Nonionina subgranosa* Egger (1857), both from the Miocene of Bavaria, Germany. Since cribrate apertures are an unknown feature in true *Nonion*, a new generic name is herewith proposed, with *Nonionina heteropora* Egger, 1857 (N. Jahrb. f. Min., p. 300, pl. 14, figs. 19–21) as genotype. Type locality: Miocene, Hausbach near Ortenburg, Bavaria, Germany.

SOCIETY OF VERTEBRATE PALEONTOLOGY

PERMIAN FISHES FROM THE KAIBAB FORMATION OF ARIZONA

BY L. HUSSAKOF

During the past few years, fish remains have been discovered in the Kaibab formation of Arizona. Most of the specimens thus far collected are teeth of sharks, with a crushing type of dentition, and shark spines. They are rare in the formation, occur singly, and are generally collected from the hard limestrone strata in an imperfect condition which makes possible only generic identification.

This is the first record of the occurrence of this Permian fish fauna. The forms noted include the following: *Deltodus mercurii* Newberry, *Psephodus*, a new species of *Janassa* (Petalodontidae), which is described from a tooth, a large fin-spine of *Hybodus*, and detached teeth of a ganoid, probably *Lepidotus*.

The Kaibab fish fauna shows a continuance into the Permian of some elasmobranch families especially numerous in the Carboniferous seas, a condition that has been noted in the case of some other Permian fish faunas.

SUTURE BONES: THEIR PROBABLE MODE OF FORMATION IN MAN

BY CHARLES R. NOBACK

Suture bones in man "appear to be fortuitous embryonic ossifications" . . . "appear to be due to the detachment of marginal 'islands' of ossification from the edges of the normal bones" (DeBeer, 1937). This is the generally accepted explanation for suture bone formation in the majority of cases.

Especially during the early fetal period in man the rapidly proliferating membranous calvarial bones have detached osseous islets variably arranged on their peripheral margins. These islets, which are later incorporated into the main bone, were observed to be infrequently associated with the facial bones, and they were never observed associated with the basicranial bones (Noback, 1943, Anat. Rec. 87). These islets are readily demonstrated *in situ* by alizarin red S or silver nitrate. The frequency of the distribution of these islets corresponds with the frequency of the location of the sutural bones, which are generally observed in the sutures of the calvarium, infrequently observed in facial sutures, and rarely observed in the basicranial sutures.

The hypothesis is advanced that, in man, the formation of some, possibly most, suture bones is due to the enlargement and nonfusion of these islets. Thus in man suture bones may be interpreted as persistent normally present embryonic structures. They are probably not always fortuitous ossifications or detachments. These islets are probably a morphological expression of the rapidly growing bones to encase the enlarged human brain.

FISH REMAINS FROM THE MIDDLE DEVONIAN BONE BEDS OF THE CINCINNATI ARCH REGION

BY JOHN W. WELLS

Four bone beds occur in the Columbus and Delaware formations of central Ohio. The Rocky Branch bone bed near the top of the Jeffersonville limestone in southeastern Indiana correlates with the Second Ohio bone bed at the top of the Columbus. The Kiddville bone bed in the basal part of the Boyle limestone in east-central Kentucky is correlated with the East Liberty bone bed at the top of the Columbus formation in the Bellefontaine Devonian outlier of west-central Ohio. On the basis of fish remains the Kiddville and East Liberty bone beds are thought to be much younger than the late Ulsterian and early Erian bone beds of central Ohio and may be of latest Erian (Taghanic) age.

The presence of fish remains in the bone beds has long been known, but they have never been studied in any detail. They consist of teeth, spines, dermal denticles, scales, and fragments of plates, mostly microscopic in size, none in natural association but often individually complete in themselves. Few of them can be assigned to previously known genera based upon more complete material; hence most of the 28 species, nearly all new, are placed in organ genera distributed among the following groups: drepanaspids, cephalaspids, acanthodians, arthrodirans, cladoselachians, pleuracanthodians, and rhipidistians. Practically all these fishes are believed to have lived in the nonmarine habitats of the mid-Paleozoic landmass of Cincinnatia.

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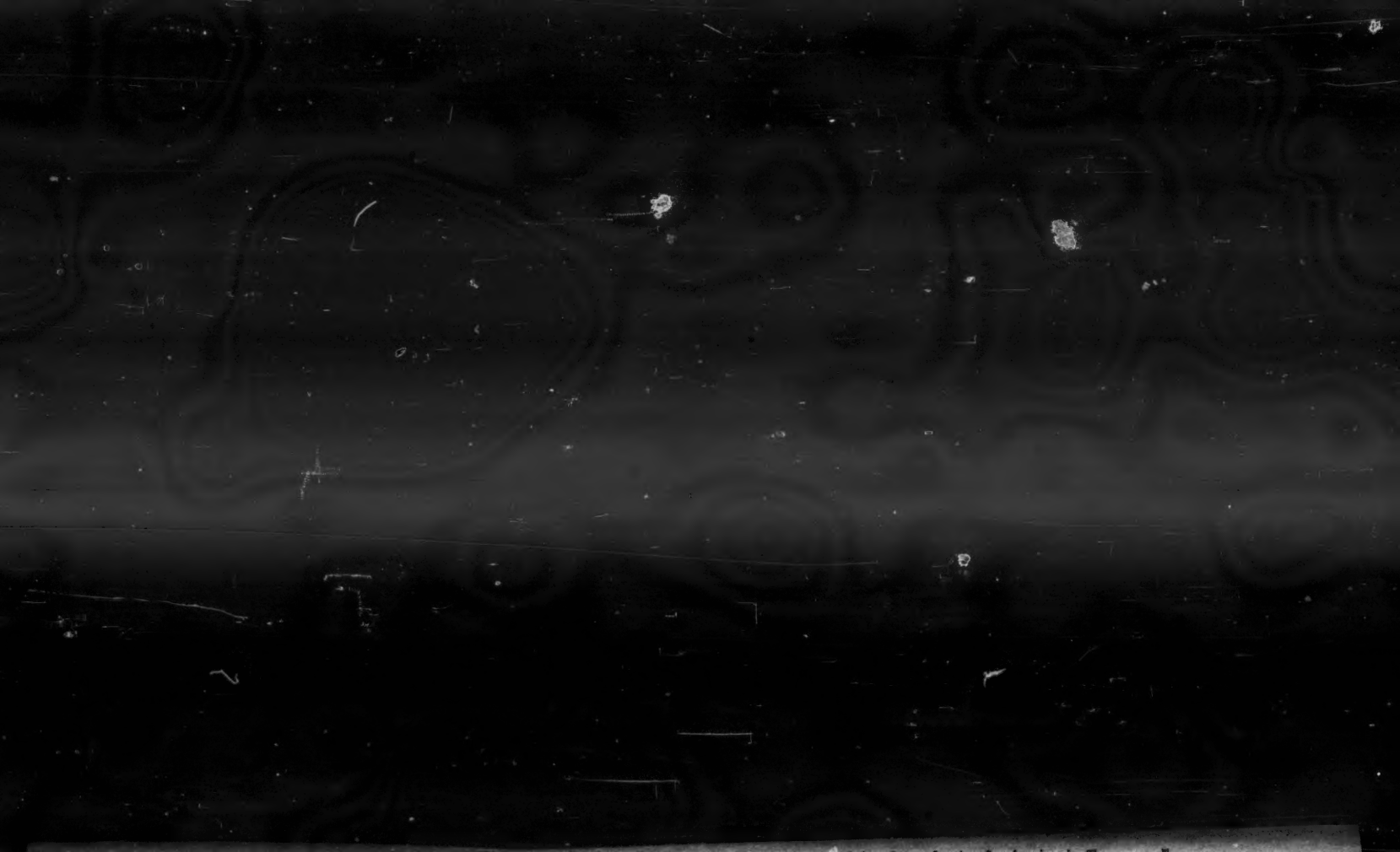
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